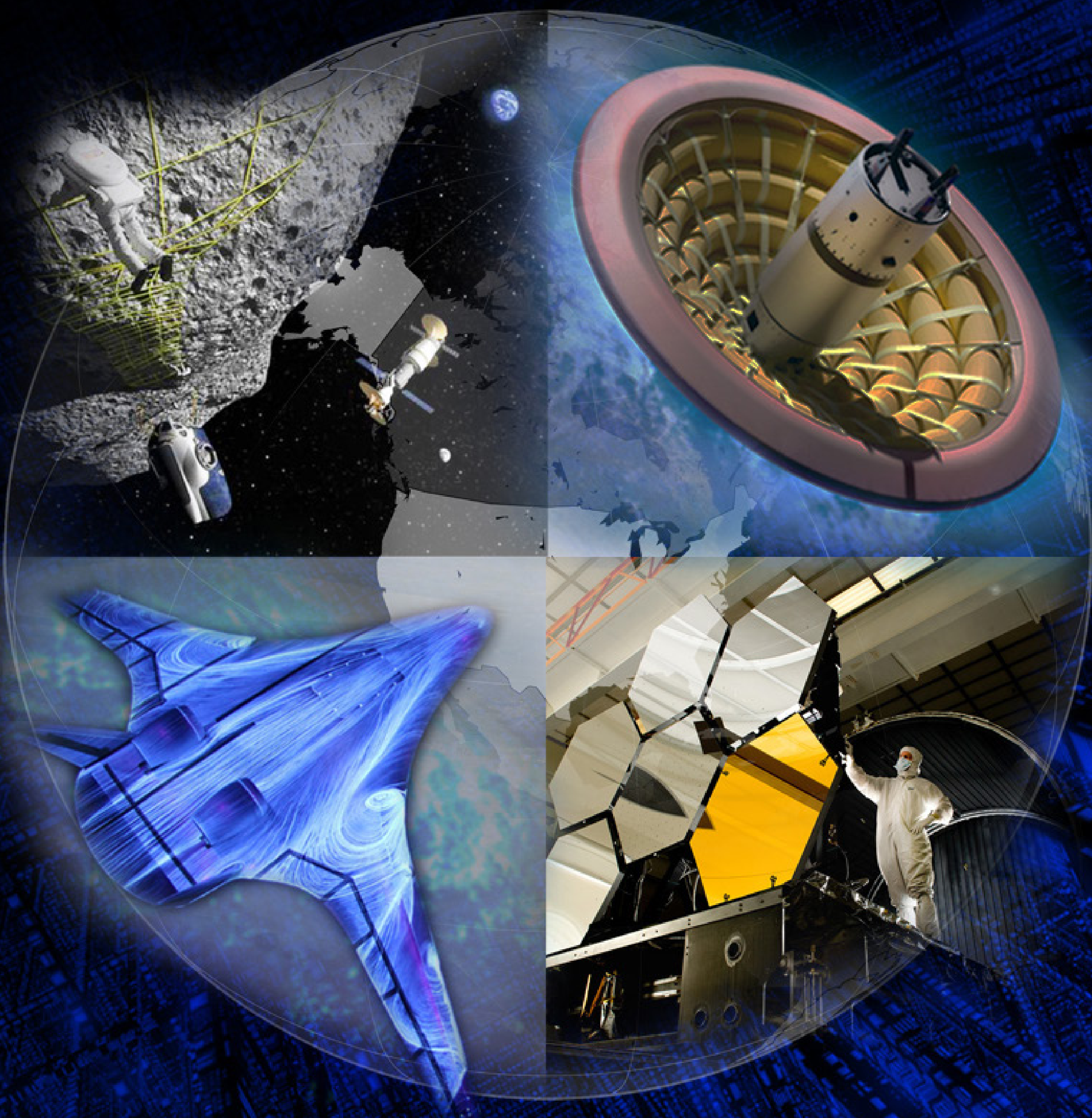
National Aeronautics and Space Administration

NASA Technology Roadmaps

TA 12: Materials, Structures, Mechanical Systems, and Manufacturing



May 2015 Draft

Foreword

NASA is leading the way with a balanced program of space exploration, aeronautics, and science research. Success in executing NASA's ambitious aeronautics activities and space missions requires solutions to difficult technical challenges that build on proven capabilities and require the development of new capabilities. These new capabilities arise from the development of novel cutting-edge technologies.

The promising new technology candidates that will help NASA achieve our extraordinary missions are identified in our Technology Roadmaps. The roadmaps are a set of documents that consider a wide range of needed technology candidates and development pathways for the next 20 years. The roadmaps are a foundational element of the Strategic Technology Investment Plan (STIP), an actionable plan that lays out the strategy for developing those technologies essential to the pursuit of NASA's mission and achievement of National goals. The STIP provides prioritization of the technology candidates within the roadmaps and guiding principles for technology investment. The recommendations provided by the National Research Council heavily influence NASA's technology prioritization.

NASA's technology investments are tracked and analyzed in TechPort, a web-based software system that serves as NASA's integrated technology data source and decision support tool. Together, the roadmaps, the STIP, and TechPort provide NASA the ability to manage the technology portfolio in a new way, aligning mission directorate technology investments to minimize duplication, and lower cost while providing critical capabilities that support missions, commercial industry, and longer-term National needs.

The 2015 NASA Technology Roadmaps are comprised of 16 sections: The Introduction, Crosscutting Technologies, and Index; and 15 distinct Technology Area (TA) roadmaps. Crosscutting technology areas, such as, but not limited to, avionics, autonomy, information technology, radiation, and space weather span across multiple sections. The introduction provides a description of the crosscutting technologies, and a list of the technology candidates in each section.

Table of Contents

Executive Summary

This is Technology Area (TA) 12: Materials, Structures, Mechanical Systems, and Manufacturing, one of the 16 sections of the 2015 NASA Technology Roadmaps. The Roadmaps are a set of documents that consider a wide range of needed technologies and development pathways for the next 20 years (2015-2035). The roadmaps focus on “applied research” and “development” activities.

TA 12 recommends novel cutting edge technologies that apply to a wide range of NASA strategic goals and Agency programs. Advances in materials, structures, mechanical systems, and manufacturing are needed to ensure that NASA and the U.S. remain the leaders in space exploration and scientific discovery. Innovative technologies in these critical areas are required to carry out future NASA missions and will strengthen the U.S. economy through science and technology developments across the many industry sectors that utilize these technologies. These innovations can fundamentally change the way things are built and dramatically reduce the time from design to production.

Four chief technical challenges for human travel to deep space (beyond the moon) are considered throughout this plan: radiation protection, mass reduction, reliability, and affordability. Radiation shielding is critical because the dose of galactic cosmic radiation (GCR) through heritage spacecraft structural systems far exceeds human limits for a trip to an asteroid, or to Mars. Mass reduction is essential since it will take as much as 300 pounds (lbs) of chemical propellant to move one pound of vehicle from Earth to Mars orbit and back. NASA has learned much regarding long-term structural and system reliability from the International Space Station (ISS). However, reliability will need to advance to another level for us to travel into deep space where resupply for repair will not exist. Technological advancements are vital to improvements in affordability that will serve to accelerate technology transition to NASA programs. Additionally, the roadmap although very broad, targets technology areas where the disciplines can be integrated in order to accelerate the technology adoption life cycle across the life cycle of innovation, materials, design, manufacturing, and commercialization.

The TA 12 roadmap will provide technological progress through partnerships with other government agencies, industry, and academia. The roadmapping effort will identify and leverage industry and commercial cutting-edge technologies that advance NASA and national interests. The innovative Materials, Structures, Mechanical Systems, and Manufacturing technology area continues to inspire the next generation of scientists, technologists, and engineers.

Materials are the enablers behind the structures, devices, vehicles, power, life support, propulsion, entry, and many other systems that NASA develops and uses to fulfill its missions. New materials are required as are materials with improved properties, combinations of properties and reliability. The computational techniques for designing, improving, and understanding materials behavior require continued enhancement. The combination of computation and experiment is powerful and will accelerate the next step in materials development.

Structures represent the design and analysis content to apply materials in a manner that results in certification for the intended environments. NASA’s vision to extend exploration into deep space requires challenging structural innovation. NASA must do much more with much less. In order to succeed, NASA must engage in multifunctional combined system capability and smart structural designs. Certification and sustainability throughout the mission are often some of the most cost and time-consuming efforts in spacecraft development. Many of the structures technology advancements described herein are critical enablers to send humans into deep space.

Mechanism systems are essential to performing the functions required at virtually every stage of spaceflight operations in order to achieve specified mission objectives. Since mechanisms dictate the lifetime of a given mission, they must be designed to be robust, long-lived, and capable of performing in the harsh environments encountered in space. Embedded sensors in mechanisms will enable the acquisition of real-time data and the ability to monitor system performance, improving system reliability, and leading to improved designs. Health monitoring will give us real data from mechanisms operating in their environment, which will lead to improved confidence in analytical tools and ultimately digital design certification.

Advanced manufacturing will focus on the highest value innovative opportunities, and integration of new tools into the evolving manufacturing arena targeted at stakeholders including NASA, other government agencies, and the aerospace industry. Manufacturing technological advancements are key to bridge the gap of cross-disciplinary advances over the entire research and development (R&D) continuum from R&D to full-scale production and ensure that advanced manufacturing capabilities are available for significant improvements in cost, schedule, and overall performance. NASA participates in several initiatives designed to stimulate U.S. leadership in advanced manufacturing research, innovation, and technology.

Goals

TA 12 technology candidates address the Agency's human exploration, science, and aeronautics mission architecture needs for both enhancing and enabling technologies. These are cutting-edge technologies that directly address the four chief technical challenges in terms of architecture needs and gaps, and game-changing new technologies that will dramatically enhance mission capabilities.

TA 12 promotes U.S. innovation and industrial competitiveness by providing the means to reduce the cost and development time of materials discovery, design optimization, and manufacturing deployment. The technologies can, for example, provide higher temperature rocket engine components, radiation protection from multifunctional structures, precision large-aperture optics, and new manufacturing processes for efficiency and improved energy consumption.

NASA has an immediate need for more affordable, lightweight materials and processes across its unique missions, systems, and platforms. TA 12 supports improved alignment between technology development and product delivery for NASA exploration, science, and technology missions. NASA researchers have a unique capability in the International Space Station (ISS) national laboratory to conduct materials science experiments that cross the boundaries of materials discoveries, and engineering need-driven higher-performing materials for NASA and other national needs. This technology area offers some of the greatest potential for improvements in cost, schedule, and overall performance. Innovation in materials will result in improved performance and reliability of aerospace systems through the use of materials designed to more closely meet the needs and environments of future missions through substantial mass reductions and materials with multiple or tailored functions and capabilities. Advances in the structures area will produce robustness and superior system structural integrity required for deep space and science missions. Developments in mechanical systems will enable enhanced capabilities for deployable large precision structures and extend mechanism life in harsh environments. Advanced manufacturing will exploit the 'digital thread' that integrates and drives modern aerospace design, manufacturing, and mission execution to deal with constantly increasing complexity in hardware and missions, and significantly reduce cost and schedule. NASA is integrating the design, engineering, technology development, and manufacturing of processes, and practices, to realize the "Digital Twin." The digital twin concept is an approach to enable a suite of comprehensive multidisciplinary physics-based models that represent all of the physical materials, processes, and products, and ultimately incorporating these capabilities in the production and operation of spacecraft.

Table 1. Summary of Level 2 TAs

12.0 Materials, Structures, Mechanical Systems, and Manufacturing	Goals:	Develop materials to increase multi-functionality and reduce mass and cost (radiation protection/mass reduction challenges). Provide innovative designs and tools for robustness and superior structural integrity for deep space and science missions (reliability/mass reduction challenges). Design and develop robust, long-life mechanisms capable of performing in the harsh environments (reliability challenge). Advance new processes and model-based manufacturing capabilities for more affordable and higher performance products (mass reduction/affordability challenge).
12.1 Materials	Sub-Goals:	Design materials that have multiple tailored functions to meet specific mission needs.
12.2 Structures	Sub-Goals:	Develop lightweight, robust, multifunctional, smart structures that are reliable and predictable.
12.3 Mechanical Systems	Sub-Goals:	Improve life and reliability of mechanisms to extend the life of space missions. Improve the precision alignment capability of mechanisms to extend the capability of deployable structures.
12.4 Manufacturing	Sub-Goals:	Develop innovative physical manufacturing processes combined with the ‘digital thread’ that integrates modern design and manufacturing.

Benefits

TA 12 technology candidates not only enable future NASA missions, but they also provide spinoffs that benefit diverse sectors of the economy, increase our global competiveness, and improve quality of life. Energy efficiency and energy independence are facilitated by advanced solar-voltaic cells, superconducting alloys for reduced power transmission losses, and lighter-weight structures, which will reduce transportation fuel costs. Intelligent, “green” manufacturing, recyclable materials, and reusable structures conserve natural resources, eliminate sources of waste, and reduce life cycle costs. In addition, the cyber-physical approaches such as additive manufacturing broaden the U.S. manufacturing base and facilitate new product introduction and improvement. A pervasive use of modeling, simulation, and health monitoring technologies will revolutionize development and operation of civil aerospace systems. These technologies will enable more rapid introduction of advanced materials and structural concepts with quantified reliability, reduced maintenance costs, and increased mission safety.

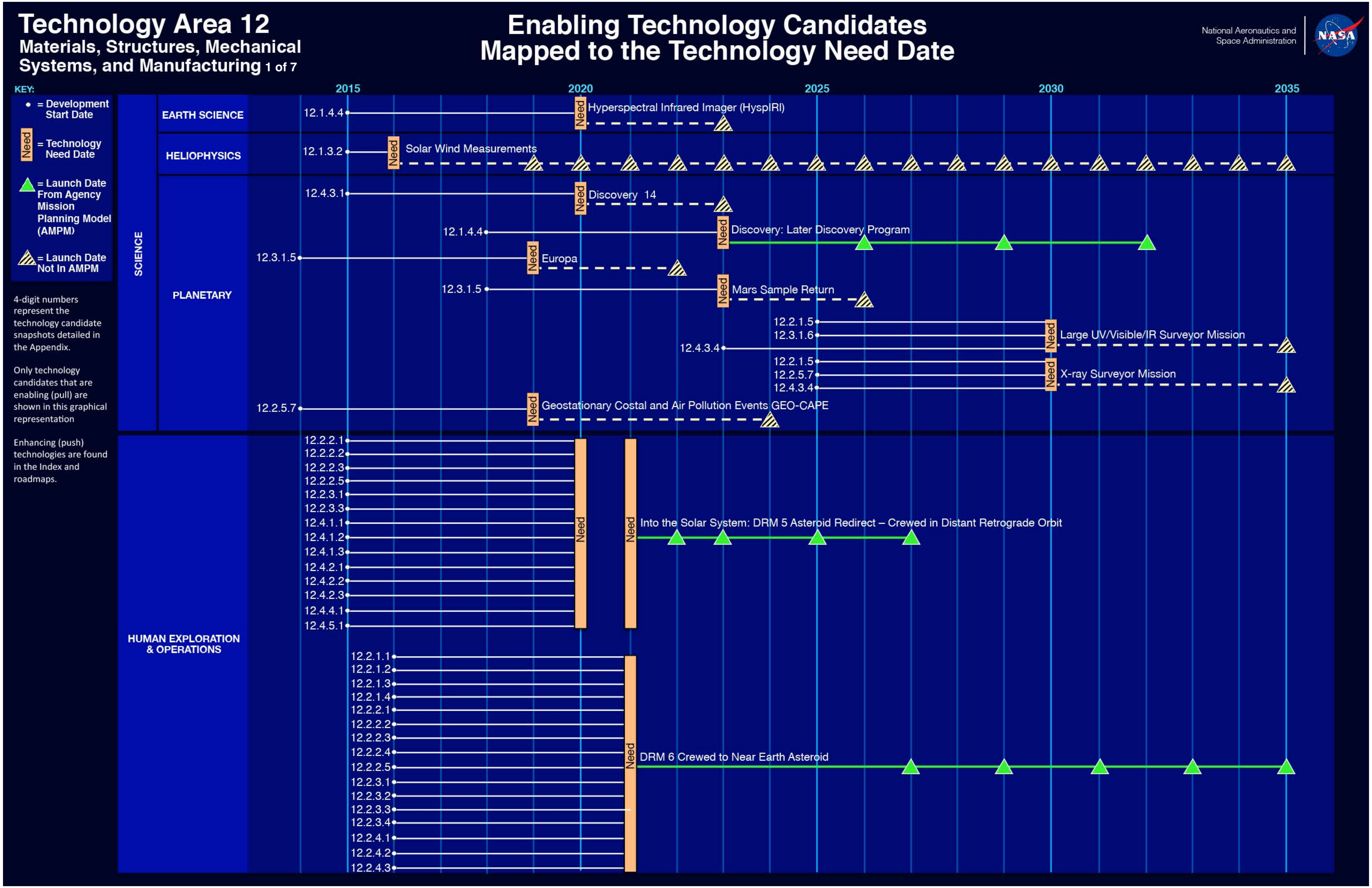
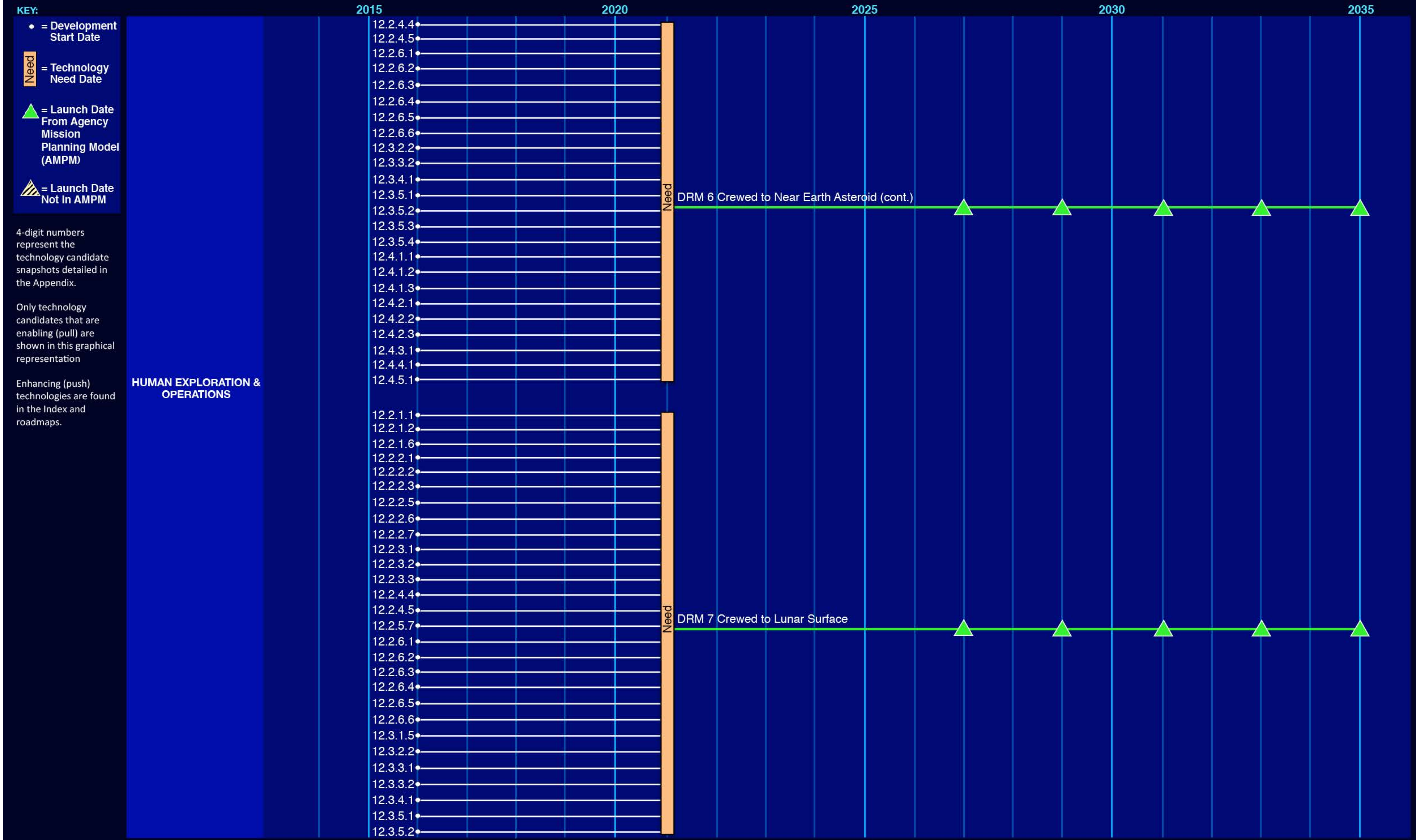


Figure 1. Technology Area Strategic Roadmap

Technology Area 12
Materials, Structures, Mechanical Systems, and Manufacturing (cont.) 2 of 7

Enabling Technology Candidates Mapped to the Technology Need Date

National Aeronautics and Space Administration



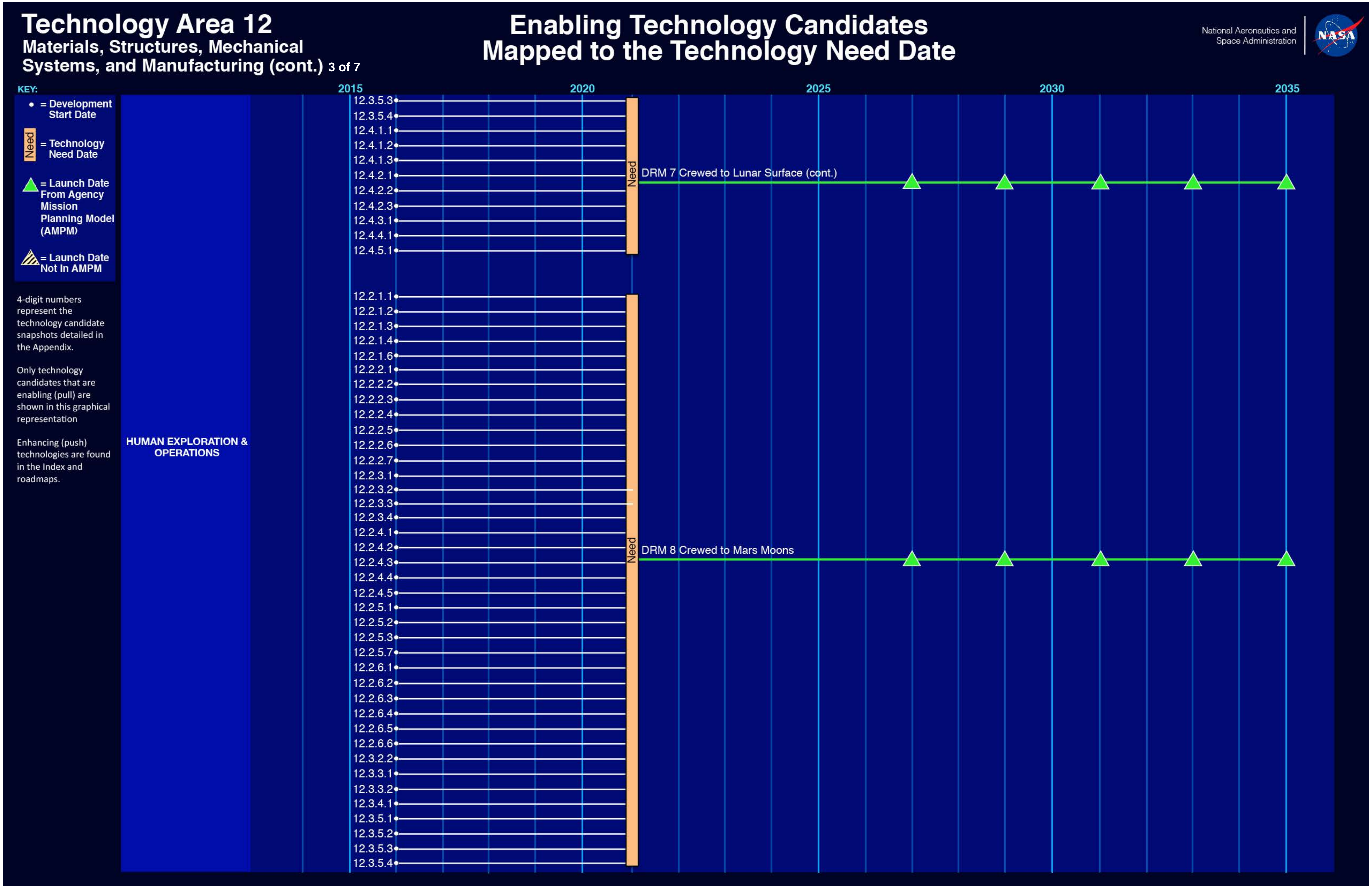


Figure 1. Technology Area Strategic Roadmap (Continued)

DRAFT

Technology Area 12
Materials, Structures, Mechanical Systems, and Manufacturing (cont.) 4 of 7

Enabling Technology Candidates Mapped to the Technology Need Date

National Aeronautics and Space Administration

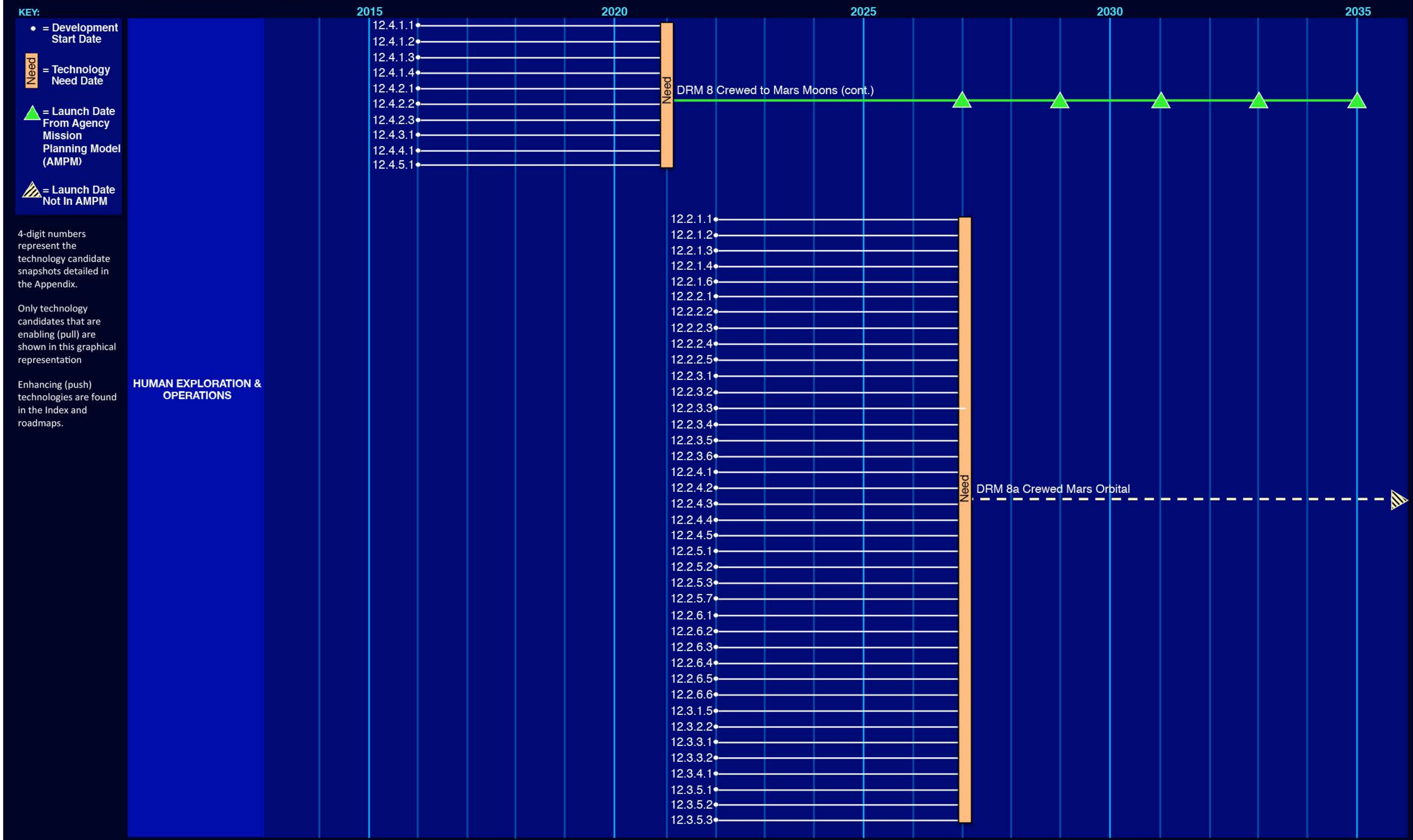


Figure 1. Technology Area Strategic Roadmap (Continued)

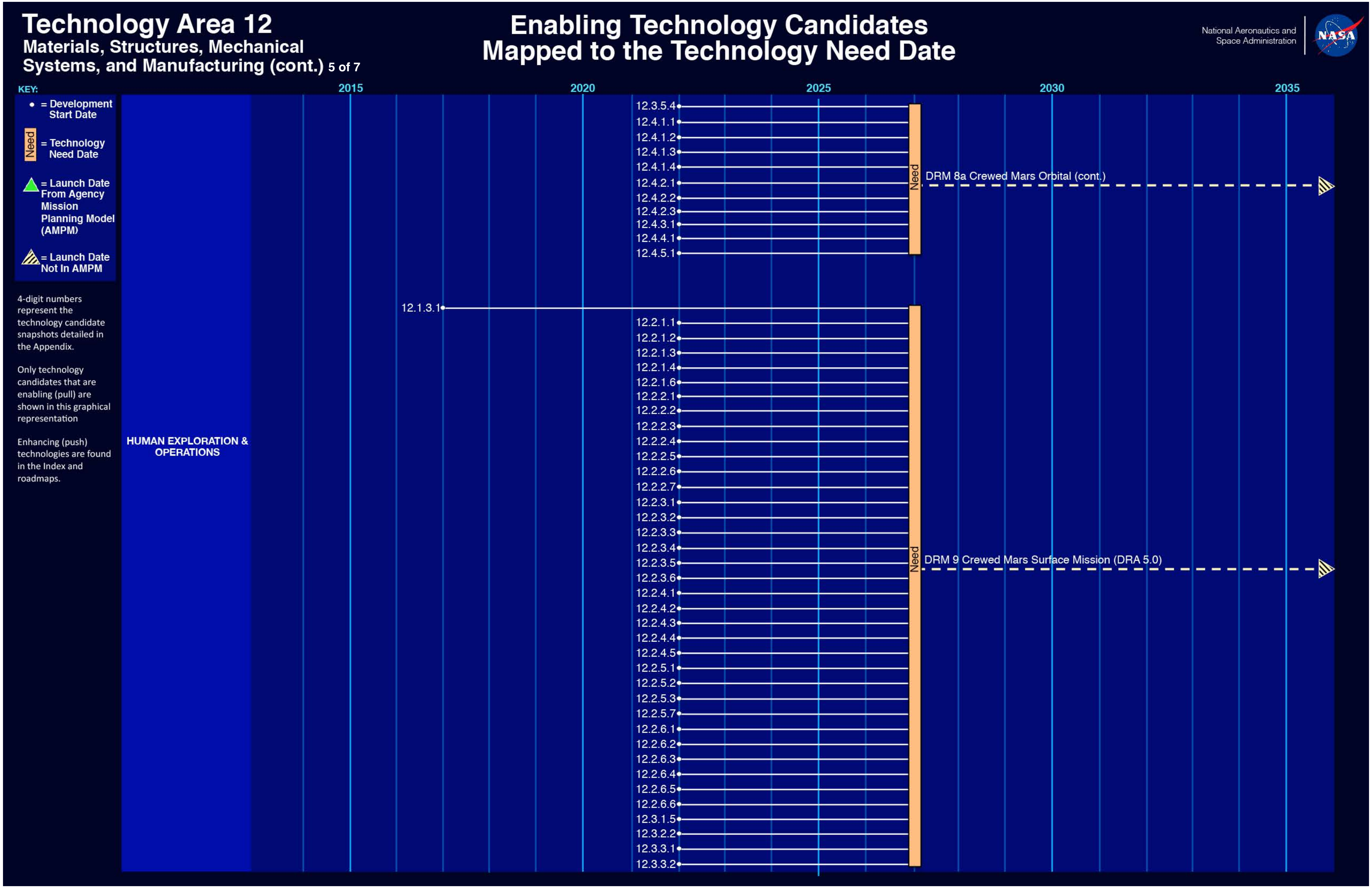


Figure 1. Technology Area Strategic Roadmap (Continued)

Technology Area 12
Materials, Structures, Mechanical Systems, and Manufacturing (cont.) 6 of 7

Enabling Technology Candidates Mapped to the Technology Need Date

National Aeronautics and Space Administration

KEY:
- • = Development Start Date
- Need = Technology Need Date
- = Launch Date From Agency Mission Planning Model (AMPM)
- = Launch Date Not In AMPM

4-digit numbers represent the technology candidate snapshots detailed in the Appendix.

Only technology candidates that are enabling (pull) are shown in this graphical representation

Enhancing (push) technologies are found in the Index and roadmaps.

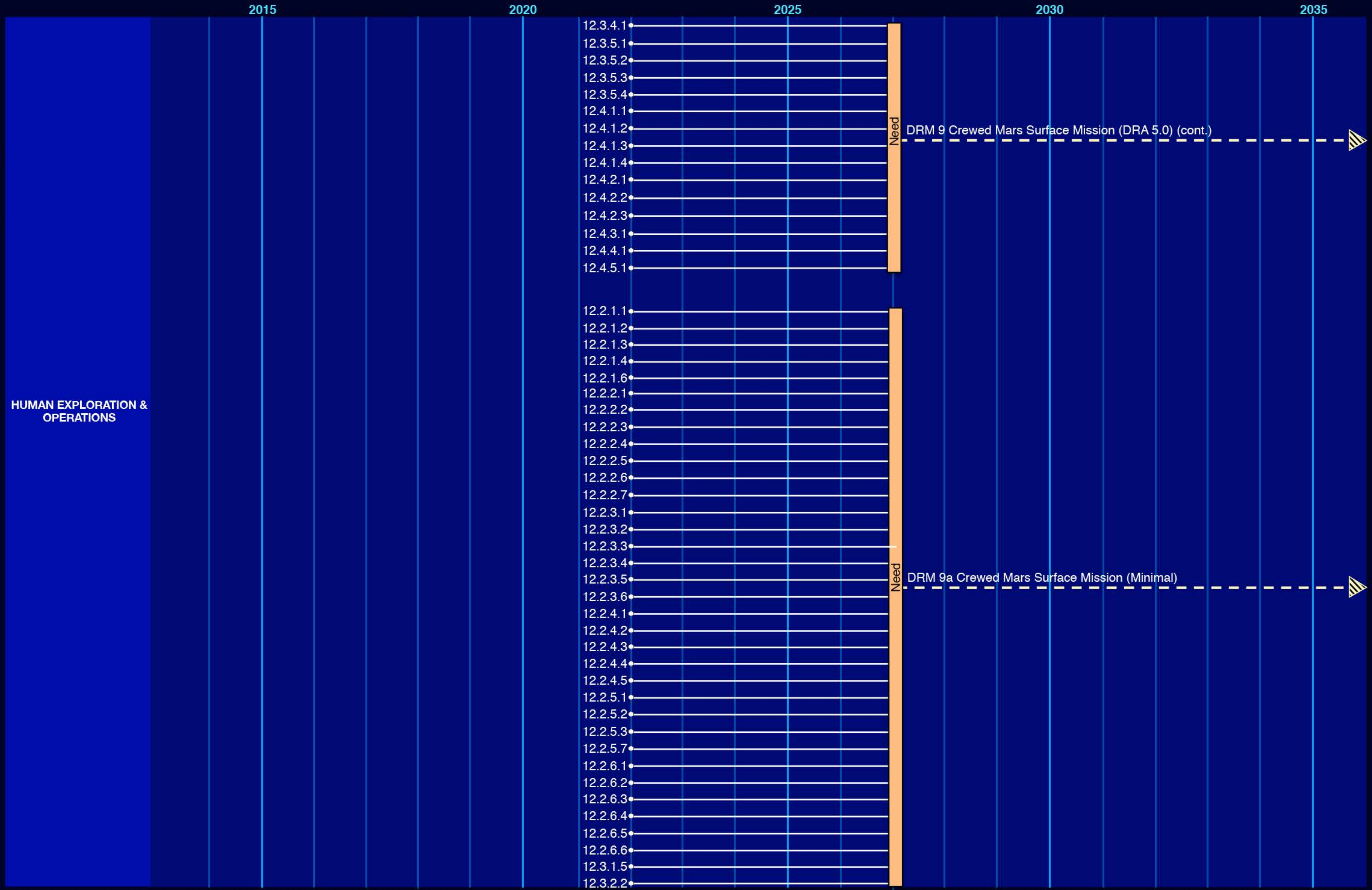


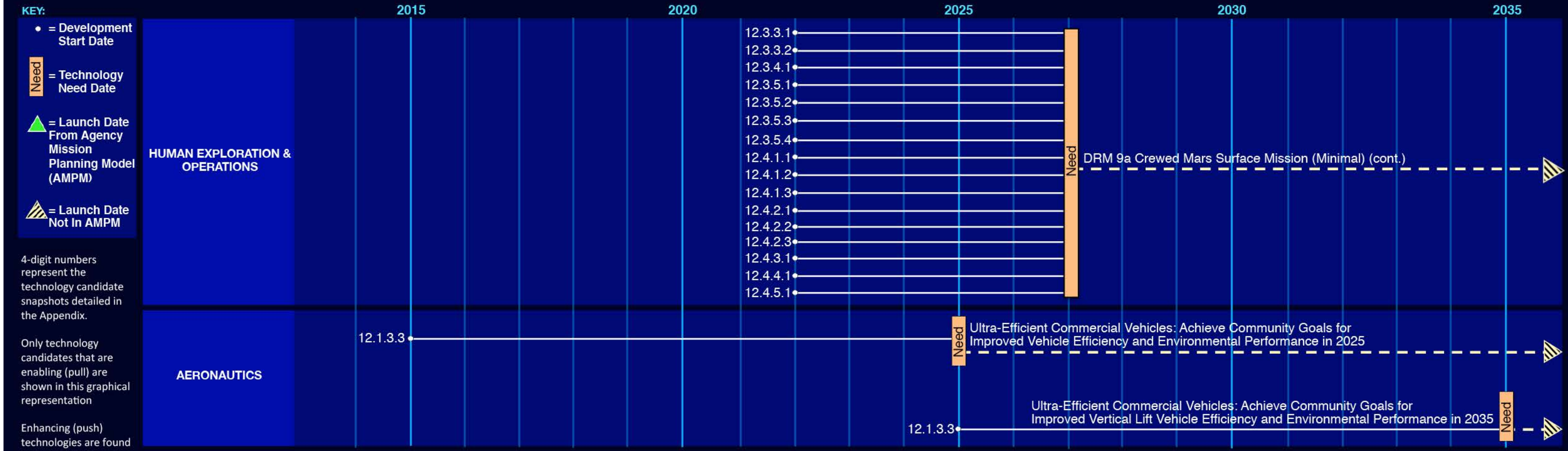
Figure 1. Technology Area Strategic Roadmap (Continued)

Technology Area 12

Materials, Structures, Mechanical Systems, and Manufacturing (cont.) 7 of 7

Enabling Technology Candidates Mapped to the Technology Need Date

National Aeronautics and Space Administration



4-digit numbers represent the technology candidate snapshots detailed in the Appendix.

Only technology candidates that are enabling (pull) are shown in this graphical representation

Enhancing (push) technologies are found in the Index and roadmaps.

Figure 1. Technology Area Strategic Roadmap (Continued)

Introduction

The NASA technology area (TA) roadmap for Materials, Structures, Mechanical Systems, and Manufacturing addresses the technology development strategy required to enable and sustain the Agency's needs in aeronautics, science, and exploration.

This technology roadmap contains overarching themes that are related to enhancing (push) and and enabling (pull) technologies and national needs. Multifunctional and lightweight are critical attributes and technology themes required by mission architecture. Affordability, certification, and reliability are technology themes that present critical technology needs to address mission gaps. NASA missions urgently need new technologies for low cost reliable modern manufacturing and materials processing capabilities. A deliberate viewpoint for many of the technologies within the roadmap is to promote the idea of innovation in materials, structures, mechanical systems, and manufacturing technologies that bring about totally new inventions or discoveries rather than improvement on an existing technology. Many of the roadmap technology candidates are directly related to national technology initiatives associated with development of materials, new energy sources, aging infrastructure, manufacturing, and environmental concerns. Figure 2 presents the Materials, Structures, Mechanical Systems, and Manufacturing technology areas.

TA 12 **Materials, Structures, Mechanical Systems, and Manufacturing**

12.1 Materials
- 12.1.1 Lightweight Structual Materials
- 12.1.2 Computationally-Designed Materials
- 12.1.3 Flexible Material Systems
- 12.1.4 Materials for Extreme Environments
- 12.1.5 Special Materials

12.2 Structures
- 12.2.1 Lightweight Concepts
- 12.2.2 Design and Certification Methods
- 12.2.3 Reliability and Sustainment
- 12.2.4 Test Tools and Methods
- 12.2.5 Innovative, Multifunctional Concepts
- 12.2.6 Loads and Environments

12.3 Mechanical Systems
- 12.3.1 Deployables, Docking, and Interfaces
- 12.3.2 Mechanism Life Extension Systems
- 12.3.3 Electro-Mechanical, Mechanical, and Micromechanisms
- 12.3.4 Design and Analysis Tools and Methods
- 12.3.5 Reliability, Life Assessment, and Health Monitoring
- 12.3.6 Certification Methods

12.4 Manufacturing
- 12.4.1 Manufacturing Processes
- 12.4.2 Intelligent Integrated Manufacturing and Cyber Physical Systems
- 12.4.3 Electronics and Optics Manufacturing Process
- 12.4.4 Sustainable Manufacturing
- 12.4.5 Nondestructive Evaluation and Sensors

12.5 Cross-Cutting

Figure 2. Technology Area Breakdown Structure (TABS) for Materials, Structures, Mechanical Systems, and Manufacturing

12.1 Materials

Materials consists of five discipline capabilities: lightweight structure; computational design; flexible material systems; environment (protection and performance); and special materials and processes. The technology capabilities for lightweight structure, flexible material systems, and environment address key near and long-term mission technology needs for advanced structures, propellant depot, heavy lift vehicle, and critical concepts for human radiation protection. Special materials and process capabilities will fulfill a spectrum of unique technology needs for both human and science missions. Computational materials capabilities are truly game changing; these advanced technologies will be used for efficient materials design, enable critical understanding of new materials required for robust and cost effective certification methods, and provide critical new technologies for game changing sustainment methods that will ensure safe and reliable missions.

Materials technologies can be grouped into the following general categories:

- **12.1.1 Lightweight Structural Materials:** Materials that can reduce the mass of structures include composites, especially polymer matrix composites (PMCs), for tanks, structures, and multifunctional materials, incorporate sensing functions to monitor environment or the state of the material, or incorporate repair or healing mechanisms.
- **12.1.2 Computationally Designed Materials:** Computational design of materials covers three major areas: prediction of life, design of materials with tailored or improved properties, and guided experimental validation. Improved properties and predictable performance will decrease developmental and operational costs while improving safety.
- **12.1.3 Flexible Material Systems:** Flexible materials covers textiles and other materials that can be used for inflatable life support structures, heat shields, and to make morphing structures for vehicles or deployed structures.
- **12.1.4 Materials for Extreme Environments:** Materials that protect against the harsh (high and low temperature, pressure, corrosive, radiation, and combined) environments of space or vehicle operating conditions, including propulsion environments, include materials used for heat shields, especially advanced ablators, cryo-insulation, and high temperature materials including ceramic matrix composites (CMCs), ultrahigh temperature ceramics, advanced alloys, coatings, insulators, and radiation hardened electronics.
- **12.1.5 Special Materials:** Special materials are those that are used for specialized functions such as space suits, optically transparent windows, power generation, and energy storage.

12.2 Structures

Structures consists of six capabilities: lightweight concepts; design and certification methods; reliability and sustainment; test tools and methods; innovative, multifunctional concepts; and loads and environments. Game-changing technologies exist in each of the capabilities that will enable future deep space missions, next-generation aeronautic proficiencies, long-term space travel, and science missions. Advanced concepts and multifunctional structural systems will provide reductions in mass and volume for next generation vehicles. Innovative model-based technologies are fundamental to the improvement of: a) the design, development, test, and evaluation (DDT&E) process (cost, schedule, integrity, and reliability); b) the flight certification process (cost, schedule, and rigor); and c) vehicle sustainment throughout its service life (safety, autonomy, and reliability). These hardware and methods technology products must be developed to achieve NASA's vision for future aeronautics and space missions. The culmination of these products is an end-to-end digital technology called the Virtual Digital Fleet Leader or Digital Twin. This integrated collection of technologies provides a digital representation of the flight system with comprehensive diagnostic and prognostic capabilities to enable efficient development and certification as well as safe, autonomous operation throughout the service life of system. Structures technologies can be grouped into the following general categories:

- **12.2.1 Lightweight Concepts:** Structurally efficient systems using new and innovative approaches such as structural geometries enabled by new material systems to develop the mass reduction necessary in large structures for deep space missions.
- **12.2.2 Design and Certification Methods:** Incorporation of model-based materials, manufacturing, and structural design methods with rational testing approaches to improve design and certification capabilities such as cost, schedule, and structural integrity.
- **12.2.3 Reliability and Sustainment:** Integration of physics-based analysis and design methods to develop a stochastic understanding of structural response for autonomous monitoring and repair.
- **12.2.4 Test Tools and Methods:** Integration of advanced analytical tools and sensory systems to advance certification, reliability, and sustainment for deep space.
- **12.2.5 Innovative, Multifunctional Concepts:** Innovative and multifunctional technologies combine subsystems/capabilities into the structure for mass and volume savings beyond heritage space vehicles for NASA missions.
- **12.2.6 Loads and Environments:** Deterministic and stochastic technologies to more accurately address the thermal and mechanical application of launch, transport, and quiescent loads to the primary and secondary structures and supported systems of deep space vehicles.

12.3 Mechanical Systems

Mechanical Systems consists of six capabilities: 1) deployables, docking, and interfaces; 2) mechanism life extension systems; 3) electro-mechanical, mechanical, and micromechanisms; 4) design and analysis tools and methods; 5) reliability, life assessment, health monitoring; and 6) certification methods. Mechanism technologies primarily overcome physical limitations due to launch vehicle constraints and extending mechanism life in harsher environments such as regolith and cryogenic. Deployable methods, especially for precision large rigid structures or flexible materials are the enabling force behind developing the larger systems needed to attain advancements in science and engineering of today and tomorrow. In addition, micro-mechanisms foster a safer environment for our missions to land and explore new worlds. Exciting systems that keep NASA's finger on the pulse of each vehicle are included in the stepping-stones of interrelated correlated analysis system and digital certification and their eventual pinnacle of the Virtual Digital Fleet Leader.

Mechanical systems technologies can be grouped into the following general categories:

- **12.3.1 Deployables, Docking, and Interfaces:** Mechanisms to overcome the constraints of launch vehicle fairing sizes and common universal interchangeable interfaces.
- **12.3.2 Mechanism Life Extension Systems:** Mechanisms that can survive in harsh environments with high reliability.
- **12.3.3 Electro-mechanical, Mechanical, and Micromechanisms:** Mechanisms that allow robotic manipulation and servicing of vehicles.
- **12.3.4 Design and Analysis Tools and Methods:** Progressive improvements in analysis tools that lead to a single model being used for solving multi-objective problems.
- **12.3.5 Reliability, Life Assessment, and Health Monitoring:** Health and life monitoring of mechanical systems that aid in mechanism life predictions.
- **12.3.6 Certification Methods:** Progressive improvements in analytical modeling leading to the digital certification of hardware.

12.4 Manufacturing

Manufacturing consists of five capability areas: 1) manufacturing processes; 2) intelligent integrated manufacturing and cyber physical systems; 3) electronics and optics manufacturing process; 4) sustainable manufacturing; and 5) nondestructive evaluation. The manufacturing area provides the most important link between technology invention, development, and application. Emphasis is placed on emerging technologies for aerospace centric processing methods, virtual manufacturing methodology, environmentally forward-looking manufacturing, and the transformation of science and technology into manufacturing processes and products. Developing and demonstrating manufacturing technologies enables continually increasing technology readiness needed for NASA to propel promising technologies into cost-effective applications and sustainable missions. One of the most important considerations of any technology program is the ability to accelerate and mature technologies to practical applications.

Manufacturing technologies can be grouped into the following general categories:

- **12.4.1 Manufacturing Processes:** High performance materials coupled with new high efficiency manufacturing processes to enable more rapid production, increased performance, and reduced costs.
- **12.4.2 Intelligent Integrated Manufacturing and Cyber Physical Systems:** Complex systems and digital data in manufacturing to enable highly integrated manufacturing and design of advanced products across the entire life cycle, including materials characterization, manufacturing processes, model-based predictions, and analysis and operations throughout design, engineering, manufacturing, and the supply chain.
- **12.4.3. Electronics and Optics Manufacturing Process:** Methods to Improve electronic process production speed, design for extreme environment reliability and power efficiency, and to make larger optical systems with lower areal density, and more precise and smoother surface figures for increasing aperture size for next generation space vehicles and science instruments.
- **12.4.4 Sustainable Manufacturing:** Methods to manufacture products with minimal negative environmental impacts. This technology area focuses on technologies that reduce or eliminate the use of hazardous materials in production processes; removing hazardous materials such as hexavalent chromium and volatile organic compounds from manufacturing activities such as painting, coating, and cleaning.
- **12.4.5 Nondestructive Evaluation and Sensors:** Techniques and physics-based computational models that assess the as-fabricated structures for size, location, and orientation of manufacturing defects; and provide capabilities for optimizing the inspection process to guarantee identification of flaws of interest.

TA 12.1: Materials

Materials are enabling or critical technologies for most aerospace vehicle systems. Material properties and capabilities provide the form and function to structures, sensors, thermal, and other protection and management systems, safety and life support systems, power generation and energy storage systems, and many other systems. The issue of vehicle mass is always of importance, and thus materials need to have the desired functions coupled with low overall mass. Developing materials with improved properties directly aimed at upcoming mission needs is critical to the success of future missions. The breadth of material types and applications is so broad that it is necessary to ensure that NASA develops materials that will reduce risk in or enable upcoming missions. The materials section seeks to link materials development needs with the mission needs from human exploration, science, and aeronautics missions. This section is subdivided to address the needs of lightweight structures, computational design materials, flexible material systems, environment, and special materials.

Table 2. Summary of Level 12.1 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
12.0 Materials, Structures, Mechanical Systems, and Manufacturing	Goals:	Develop materials to increase multi-functionality and reduce mass and cost (radiation protection and mass reduction challenges). Provide innovative designs and tools for robustness and superior structural integrity for deep space and science missions (reliability and mass reduction challenges). Design and develop robust, long-life mechanisms capable of performing in the harsh environments (reliability challenge). Advance new processes and model-based manufacturing capabilities for more affordable and higher performance products (mass reduction/affordability challenge).
Level 2		
12.1 Materials	Sub-Goals:	Design materials that have multiple tailored functions to meet specific mission needs.
Level 3		
12.1.1 Lightweight Structural Materials	Objectives:	Develop technologies necessary to build efficient, optimized structures.
	Challenges:	Composites that can be made by out-of autoclave processes. Understanding and manipulating composition, processing, and microstructure.
	Benefits:	Provides lightweight composite and metallic structures needed to deliver products.
12.1.2 Computationally-Designed Materials	Objectives:	Accelerate materials development and predict long-term behavior.
	Challenges:	Integration of physics-based models of materials at multiple length scales with new experimental capabilities to fully capture the relationship between processing, microstructure, properties, and performance for structural and multifunctional materials. Computer power.
	Benefits:	Builds the essential physics-based understanding needed to rapidly develop new materials that are optimized for their intended use and ensuring extreme reliability in complex systems through the Virtual Digital Fleet Leader concept. Provides prediction of materials behavior based on first principles, backed up by experiments, rather than generated completely by experimental data. Characterizes multifunctional materials relevant to the phenomena of interest.

Table 2. Summary of Level 12.1 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
12.1.3 Flexible Material Systems	Objectives:	Develop mass efficient materials solutions for long-lifetime, high-volume habitats.
	Challenges:	Efficient stowage and deployment strategies, high strength and stiffness, and damage resistance.
	Benefits:	Provides lightweight deployed human habitats for space or Mars surface and large space and lunar or planetary-based observation platforms. Provides materials for efficient transfer of photon momentum to enable solar sail propulsion. Provides shape-morphing materials for a variety of applications, i.e., control surfaces, deployable reentry vehicles, expandable habitats, and deformable mirrors.
12.1.4 Materials for Extreme Environments	Objectives:	Protect humans, structures, and devices from thermal or extreme environments.
	Challenges:	Materials shield to reduce ionizing radiation.
	Benefits:	Enables human radiation protection for deep space travel. Provides more reliable and efficient materials for cryoinsulators, with increasing R-value, lower densities, and reduced thicknesses. Provides materials that enable high performance structures capable of operating at ultra-high temperatures and/or reactive environments. Provides protection from external environments and specific functions for surfaces. Provides radiation-hardened electronic materials (including semiconductors, solders, connectors, contacts, and capacitor materials) that can operate over a wide range of temperatures. Provides materials that combine resistance to extreme thermal, chemical (corrosive), and pressure environments.
12.1.5 Special Materials	Objectives:	Provide special functions to protect systems or enable missions.
	Challenges:	Protecting electronics or other systems from radiation. Providing optically transparent materials that are low density.
	Benefits:	Provides optical materials for high-strength, lightweight, low-scatter windows for habitat and observation platforms and deployable, shape-changing solar concentrators for power and thermal energy. Provides mass efficient and volume efficient, flexible space suit materials with self-healing functions. Provides material systems to efficiently generate power and store energy in space.

TA 12.1.1 Lightweight Structural Materials

Technical Capability Objectives and Challenges

Large lightweight structures require materials and processing technologies with capabilities beyond the state of the art. Currently, the polymer matrix composite properties available by autoclave processes cannot be achieved. Many materials in systems only perform one major function and thus multiple materials may be required. Mass and complexity can be decreased if functional performance of a system through material design can be achieved. This requires an understanding and manipulation of composition, processing, and microstructure. Similarly, materials that incorporate sensing functions can decrease mass while improving reliability and safety. Further in the future are materials that can heal themselves after limited damage or incorporate a repair mechanism without significant added mass. The overall mass of a structure can be reduced by any of these material classes by reducing the mass of materials having the required properties or by multiplicity of systems and devices.

Benefits of Technology

Lightweight structures provide significant mass decreases while smart and self-healing materials can improve mission safety enhancing future exploration and science missions.

Table 3. TA 12.1.1 Technology Candidates – not in priority order

TA	Technology Name	Description
12.1.1.1	Out of Autoclave Material Systems Resins/Adhesives/Fibers	Resins, adhesives, and fibers whose properties result in large monolithic composite structures that have required performance for space applications.
12.1.1.2	Low Mass, Multifunctional Materials	Materials that perform multiple functions in one structure through control of microstructure, composition and architecture. See also 9.1 for description and requirements of multifunctional materials for entry, descent, and landing (EDL) systems.
12.1.1.3	Smart Materials	Materials that incorporate sensing functions with required mechanical and physical properties. See also 9.1 for description and requirements of multifunctional materials for EDL systems.
12.1.1.4	Self-Healing/Repair Materials	Materials that incorporate mechanisms that replace or that can be used for fast in-situ repair of damaged material.

TA 12.1.2 Computationally-Designed Materials

Computational design will accelerate the development of both structural and multifunctional materials and enable prediction of long-term behavior by understanding the relationships between processing, microstructure, properties, and performance. Numerous mechanisms exist across the range of length and time scales involved; methodologies must be developed and validated to simulate operative mechanisms across these scales.

Technical Capability Objectives and Challenges

The objective of this emerging technology is to design materials that are optimized for their intended usage, accelerate materials development, and predict long-term behavior, such as reliability, through basic understanding. Hence, the focus is development and integration of physics-based models of materials at multiple length scales with new experimental capabilities to fully capture the relationship between processing, microstructure, properties, and performance for structural and multifunctional materials.

Computational abilities are growing rapidly but there is still a significant challenge in modeling complex systems, predicting lifetimes, and understanding the relationships between composition, processing and structure, and properties. With more computer power will come the ability to model on larger scales and longer times than the current maximum capability of ~1 billion atoms and 1 microsecond. Computation needs to be done in conjunction with experiment but improved computation can significantly decrease the amount of testing that must be done.

Simulation methods can span nearly 10 orders of magnitude in length scale and 15 orders of magnitude in time scale. As a result, multiscale simulation methods must be developed to bridge nano-, meso- and micro-scale regimes. Nano-scale simulation methods such as molecular dynamics can be used to approximate processes at length scales that are not readily attainable by physical experiment. Quantitative correlation of high fidelity nano-scale simulation with complex physical damage modes needs to be overcome. Meso-scale simulation methods enable detailed simulation of volumes of material that are orders of magnitude larger than are accessible using nano-scale methods; development and validation of the, often, ad hoc rules approximating the internal interactions remains to be overcome. Micro-scale simulation methods, usually continuum-based, remove many of the complexities and reduce computational costs that are inherent to both the nano-scale and meso-scale simulation methods. These methods can consider statistically significant numbers of grains or fibers and can be used to evaluate the effects of material microstructure on macro-scale response. See TA 11.3.7 Multiscale, Multiphysics and Multifidelity Simulation for these technologies.

Computational modeling of synthesis and microstructural evolution in advanced materials will reduce reliance on experimentation while accelerating the implementation of new materials. Knowledge gained will aid in prediction of reliability and mechanical properties. Currently models only exist for equilibrium phases in well-characterized materials, and are only applicable for simple thermal profiles. Models for complex and multifunctional material systems and thermal histories are a significant challenge.

Process modeling enables the development of predictive relationships between processing parameters, materials, and final part quality. These methods are particularly important to support new advanced processing techniques such as three-dimensional (3D) printing and additive manufacturing. Challenges include development and integration of these models with advanced manufacturing techniques.

Methods for material characterization relevant to each material simulation length scale are needed for development of input parameters, support of simulation validation, and quantification of uncertainty in the simulations. They also offer the promise of discovery of mechanisms and phenomena that have not been predicted. The use of facilities that offer high resolution imaging at very small scales will be needed. Predictive computational materials need to be able to provide a means of predicting materials behavior based upon first principles, backed up by experiment rather than generated completely by experimental data. The challenges are developing the algorithms, developing the understanding of how to model the behavior of complex material systems, quantification of uncertainty propagation, verification and validation of simulations, and computing power required. Predictive computational materials are a key enhancing capability for all NASA missions.

Benefits of Technology

These technologies will enable the Agency and the Nation to develop future generation materials and build the essential physics-based understanding needed to rapidly develop new materials that are optimized for their intended usage and to ensure extreme reliability in complex systems through the Virtual Digital Fleet Leader concept.

Table 4. TA 12.1.2 Technology Candidates – not in priority order

TA	Technology Name	Description
12.1.2.1	Predictive Computational Materials	Multiscale (nano-, meso-, micro-) modeling linking atomistic to continuum scales. Optimized materials with degradation understood and predicted throughout their service lives.
12.1.2.2	Computational Materials Design	Multiscale (nano-, meso-, micro-) modeling linking atomistic to continuum scales. Computational design models for design of structural, thermal, and functional materials.
12.1.2.3	Experimental Verification Technique	Characterization techniques for materials at length scales that allow for verification of nano-, meso-, and micro-scale models.

TA 12.1.3 Flexible Material Systems

Flexible materials will allow large systems to be stored in minimal space and deployed or inflated as needed. There are issues with stowage and deployment strategies, material properties, damage resistance, and mass. Shape morphing materials that can be reconfigured are being considered for structures but there are issues with cycling, power required and the speed of change, and the amount of shape change that can be achieved. Solar sails still need improved efficiency, increased lifetime, and reduced mass. Inflatable or deployed heat shields are under development but improvements in material properties are still required.

Technical Capability Objectives and Challenges

The focus of flexible material systems is the identification of soft goods or flexible systems that enable the assembly of expandable structures from a small volume to a larger volume through the combined use of rigid linkages and joints with soft thin shells or membranes. The objective of this technology is to offer an increased volume, lower mass solution than rigid metal or composite structures through a reliance on the ability to minimize weight and stowed volume without sacrificing operational functionality and reliability. Technology solutions require low-density flexible materials for efficient stowage with deployed systems possessing high strength and stiffness for applications ranging from satellite booms and solar arrays to the construction of temporary shelters and inflatable thermal protection systems. Technology product areas include materials for expandable habitats that leverage proven flexible, soft goods technologies.

Benefits of Technology

The benefits of flexible materials include reducing mass and increasing lifetime of systems while maintaining required performance properties.

Table 5. TA 12.1.3 Technology Candidates – not in priority order

TA	Technology Name	Description
12.1.3.1	Structural Textile Material	Structural textile material that provides shape and integrity to inflatable habitats and deployable structures. See also 9.1.1.
12.1.3.2	Ultra-Lightweight Flexible Material	Ultra-lightweight substrate that is an efficient photon energy transducer. More mass efficient than metalized films with sufficient thermal and mechanical durability and flexibility for packaging, deployment, and a long-duration mission. Refer to 2.2.2 for further descriptions of materials suitable for solar sails.
12.1.3.3	Smart Flexible Material	Fabrication or processing of material that will change shape according to need. This material may incorporate multiple functions like sensing and solar or space radiation shielding with required mechanical and physical properties. The material includes shape memory alloys, shape memory polymers, bimetal, piezoelectric materials (piezoeolectric (PZT) laminates or polyvinylidene fluoride (PVDF)), phase change materials, photo-active-actuators, and/or magnetostrictive material (See also 9.1.1 for special requirements for high temperature smart flexible materials).

TA 12.1.4 Materials for Extreme Environments

Materials that protect humans, vehicles, and systems from the environments experienced in space, during entry, on planets, or in other extreme environments, are needed. Efficient cryo-liquid storage tanks require the development of low-density and thin cryo-insulators. Considerable advances have been made in heat shield materials and in insulators, but the push is always for more reliable and efficient materials. Opacified fibrous insulation with extreme temperature, 1,650° Celsius (C), must be developed as well as fabrication techniques for large-scale systems and relevant flight demonstrations. Very high-temperature materials with excellent resistance to corrosion and erosion are required for propulsion and some leading edge applications as well as hot structures. Ceramic matrix composites and advanced alloys have shown great promise but there are still issues with performance and reliability. Coatings can solve many problems but they must be durable, compatible with the substrate, and provide the specific performance. Exploration of places in the solar system that are very cold, very hot, and have high radiation environments require the development of radiation-hardened electronic materials that can operate over wider temperature ranges and other materials that can withstand extreme temperatures, pressures, and highly corrosive environments such as the Venus atmosphere or extreme environment locations on Earth or on other planets.

Technical Capability Objectives and Challenges

The objective of environment protection and performance is to develop the materials technologies necessary to fabricate functional and structural materials capable of maintaining essentially original properties after a defined time period in an extreme environment. The extreme environments encountered include thermal, cryogenic to 2,000° C; radiation including ultraviolet, protons, neutrons, galactic cosmic rays, ions, and solar particles; micrometeoroids and orbital debris; atomic oxygen; both high and low pressures in inert and oxidizing or caustic atmosphere; and regolith. Materials that will act as a shield to reduce ionizing radiation doses to crew and material are a top technical challenge.

Benefits of Technology

Materials for extreme environments provide materials that are more reliable and efficient increasing mission safety thereby enabling or enhancing NASA exploration, deep space science, and aeronautics missions.

Table 6. TA 12.1.4 Technology Candidates – not in priority order

TA	Technology Name	Description
12.1.4.1	Cryo-Insulator Material	More reliable and efficient materials for cryo insulator, with increasing R-value, lower densities, and reduced thicknesses (see also TA 14).
12.1.4.2	High/Ultra-High Temperature Material	Advanced superalloy and ceramic matrix composite, ultra-high temperature ceramic, high temperature insulator, refractory composite, and thermal and environmental coating (see also 9.1.1 for high temperature, structural materials).
12.1.4.3	Coatings	Thermal, environmental, tribological, optical, and special coatings.
12.1.4.4	Extreme Temperature/Radiation Hardened Electronic Material	Extreme temperature, radiation hardened integrated circuit material (see also TA 11.1.1).
12.1.4.5	Material for Combined Extreme Environments	Development of material that combines resistance to extreme radiation, thermal, chemical (corrosive), and pressure environments.

TA 12.1.5 Special Materials

Special materials are those that are used for specialized functions such as space suits, optically transparent windows, power generation, and energy storage. Challenges include providing optically transparent, low-density materials at required sizes. Approaches have been formulated and are under development. Next-generation space suits will require the development of durable multifunctional self-healing fibers and fabrics. Efficient, but lightweight, energy generation and power storage is critical for missions.

Technical Capability Objectives and Challenges

The objective of this area is to provide durable, mass-efficient solutions to a broad class of materials that can be used to enhance existing technologies and enable new systems that offer to expand the trade space for space and aeronautic vehicles. Protecting electronics or other systems from radiation or providing optically transparent materials that are low density is a challenge. Commercially available electronic systems with known reliability in the radiation environment could fulfill NASA mission needs without the need for additional radiation protection.

This area covers material solutions including the near-term development of more durable and fracture resistant optical materials that will provide lighter window designs; repair materials needed for in-situ repair of both metals and composite structures; and sensor materials capable of operating in extreme environments, for example, improved space suit materials that will improve protection, mobility, and durability.

More efficient, higher temperature thermoelectric and piezoelectric solid-state electric power are needed to generate electricity remotely by converting waste heat and/or mechanical strain into useful energy which, combined with advance sensors, offer autonomous sensors that will eliminate the current wiring complexity for sensor power and conditioning that limit instrumentation.

Small-sized, high-power-density, solid oxide fuel cells, capable of greater than 2 kilowatts (kW) per kilogram (kg) operation offer game-changing electrical power solutions for space, aeronautics, and commercial application.

Benefits of Technology

Special materials provide mass savings as well as improve efficiency while maintaining required system performance. These materials can enhance exploration design reference missions.

Table 7. TA 12.1.5 Technology Candidates – not in priority order

TA	Technology Name	Description
12.1.5.1	Durable Lightweight Optically Transparent Material	Optical material that can be deployed and durable materials for observation platforms with high optical performance. All materials must be lightweight. There are concepts for polymeric and glass hybrid and transparent composite systems.
12.1.5.2	Lightweight Space Suit Material	Durable material that performs multiple functions to eliminate single function layers in current suit designs. Current layers include air bladder, restraint layer, insulation, and micrometeoroid protective layer. Self-healing functions are desirable (refer to TA 6.2.1 for further EVA spacesuit descriptions).
12.1.5.3	Power Generation and Energy Storage Material	Material for fuel cells (solid oxide, polymer electrolyte membrane), batteries, capacitors, and energy harvesting devices (solar, thermal, vibration, kinetic energy).

TA 12.2: Structures

The state of the art for NASA structures can be seen as embodied in the lightweight design concepts of the modern aircraft and satellites, and the sustainment capabilities of the ISS. Prior to the ISS, crewed spacecraft were basically 30 to 60 day mission vehicles that required replacement, or inspection and service in ground depots between missions. The ISS represented a long-term space vehicle that was not necessarily focused on lower weight as it was assembled in low-Earth orbit (LEO). Deep space vehicles beyond LEO, will require significant weight reduction over the state of the art, similar to the advancements in the Apollo era, and significant increases in robustness and autonomy over the current art, similar to the advancements in the ISS era. Along with these challenges, and perhaps even more critical, is the necessary addition in leakage, damage, and radiation protection that must be accomplished while the mass reduction and structural reliability enhancements are developed.

Sub-Goals

The structures goal is to enable future human exploration and science missions to LEO, the Moon, asteroids, Mars, and deep space through lightweight, smart, and multifunctional primary and secondary structures that are highly predictable and reliable. A critical element for structures is incorporating purposefully designed materials, digitally connected manufacturing processes, and efficient sensory systems into design, analysis, and test methods for rapid design certification and sustainment of highly reliable structures. This will enable self-diagnosis to maintain and repair structural systems with little to no dependence on ground support. This capability is essential for deep space missions that will lack resupply and ground support for operations – a significant advancement beyond our current requirements.

Composite liquid hydrogen tank fiber placement

Table 8. Summary of Level 12.2 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
12.0 Materials, Structures, Mechanical Systems, and Manufacturing	Goals:	Develop materials to increase multi-functionality and reduce mass and cost (radiation protection and mass reduction challenges). Provide innovative designs and tools for robustness and superior structural integrity for deep space and science missions (reliability and mass reduction challenges). Design and develop robust, long-life mechanisms capable of performing in the harsh environments (reliability challenge). Advance new processes and model-based manufacturing capabilities for more affordable and higher performance products (mass reduction/affordability challenge).
Level 2		
12.2 Structures	Sub-Goals:	Develop lightweight, robust, multifunctional, smart structures that are reliable and predictable.
Level 3		
12.2.1 Lightweight Concepts	Objectives:	Develop concepts that are significantly lighter and/or larger scale than state of the art.
	Challenges:	Performance and reliability of advanced structural configurations. Payload envelope size constraints of launch vehicles. Deployed structure meets mission requirements. Payload geometry constraints.
	Benefits:	Increases payload to orbit and space systems that are larger and/or have lower mass, higher precision, and/or higher reliability than state of the art systems.

Table 8. Summary of Level 12.2 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
12.2.2 Design and Certification Methods	Objectives:	Provide safe and reliable designs at reduced cost for non-heritage structures.
	Challenges:	Development of a rational, risk-based design and certification method to reduce costly empirical testing. Efficient use of tests and models to introduce lightweight materials and efficient structural designs.
	Benefits:	Reduces cost and time to develop and certify flight systems and provides higher confidence in the safety and reliability of fielded systems.
12.2.3 Reliability and Sustainment	Objectives:	Integrate physics-based analysis and design methods into a stochastic understanding of structural response for autonomous life prediction, monitoring, and repair.
	Challenges:	Understanding of mechanisms for damage initiation and propagation, and structural degradation. Detect and diagnose damage and predict the structural residual life. Restore structural integrity in the most effective manner, either repair or self-repair. Characterize the damage and the structural residual life. Adjusting mission parameters to extend life or affect a repair (or a self repair) in the most effective manner.
	Benefits:	Provides better understanding of the structure on a system basis for efficiency (lighter weight, more robust, increased autonomy), the establishment of a foundation for autonomy in deep space sustainment, and the ability to develop a structural reliability that can be integrated into full-vehicle reliability throughout a mission.
12.2.4 Test Tools and Methods	Objectives:	Integrate advanced analytical tools and sensory systems to achieve efficient certification, reliability, and sustainment necessary for NASA missions.
	Challenges:	Understand vehicle response to flight environments and incorporate this information into the vehicle development process. Higher-fidelity model correlation at a vehicle system-wide level, for response control and virtual digital certification through distributed health monitoring.
	Benefits:	Provides a more physics-based understanding to incorporate flight test (mean conditions) into the certification process, reduce the certification cost and schedule for new vehicle development, and potentially a new development and certification paradigm that mixes design, analysis, prototype fabrication, and test and evaluation in an optimized development spiral.
12.2.5 Innovative, Multifunctional Concepts	Objectives:	Combine subsystems and capabilities into the structure for mass and volume savings beyond heritage space vehicles for NASA missions.
	Challenges:	Integrate subsystem components, sensors, harnesses, and thermal controls. Design and certification of multifunctional structural systems. Reconfigure or repurpose a unit or design.
	Benefits:	Optimizes multifunctional structures to integrate sub-system functionality to reduce mass and/or volume. Use modularity to reduce integration time and reduce costs and schedule. Allows performance improvements not formerly considered, such as load suppression that can be implemented with no or little mass and volume impact. Active or passive control mitigates load environments and improves structural performance.
12.2.6 Loads and Environments	Objectives:	Develop efficient mechanical (global and local static and dynamic) and non-mechanical (i.e., radiation, atomic oxygen, thermal, etc.) environments into the structural and system capabilities for future NASA missions.
	Challenges:	Modeling the effects of multiple, competing, and transient environments into design and analysis cycles. Incorporation of active sensory system response.
	Benefits:	Improves structural and system efficiency from a physics-based understanding of the constituent loads and of their integration. Decreases reduction uncertainty in the applied loads.

TA 12.2.1 Lightweight Concepts

Lightweight structural concepts are necessary to meet future mission needs in space transportation for both in-space and planetary surface systems and for future generations of efficient aeronautical systems. Present systems primarily have an aircraft heritage and use material systems with a large experience base. These systems use machined or welded light alloys, such as aluminum (Al) or aluminum lithium (Al-Li), or autoclaved composites. Future large launch vehicle or space structures require much higher structural efficiency and fewer joints to reduce mass, and concepts that can be fabricated at scales exceeding existing facilities. This applies to both dry and tank structures. For habitable volumes, the state of the art is welded aluminum such as that found in the ISS pressurized modules. Habitable volumes may be made more structurally efficient through the use of composite materials and more volumetrically efficient through the use of inflatable or expandable structures. However, there is high confidence in developing a leak-free structure from welded metallic pressure vessels, so movement to more advanced technologies as advocated in this roadmap is perceived as risky. Scale is also an issue for uncrewed space structures, and heritage concepts will be difficult to scale to large sizes due to complexity for deployment, and design issues with structural dynamics and/or achieving precise configurations for solar array structures or for large aperture antennas.

Technical Capability Objectives and Challenges

Low mass is extremely important for in-space and planetary systems because of payload mass determines the sizing of launch vehicles. These systems will result from innovative structural geometries enabled by new material systems and their cost-effective manufacture as well as the development of an understanding of their mechanics and of the technology necessary for their design, certification, and sustainment. Composite structures play an important role in developing lightweight design because they can be tailored to specific requirements. However, for non-terrestrial applications the design, certification, and sustainment approaches must be modified from their aircraft heritage, these topics are covered more fully in the next two sections. Also, as additional functions are integrated into lightweight concepts, the mass benefits increase but at the cost of increased design, certification, and sustainment complexity. Size and cost are additional criteria addressed by this set of capabilities. Manufacturing, especially for composites, is limited by available facility size and the more complicated the design, the greater the cost and difficulty of manufacturing. So concepts that are enabled by non-autoclave processing of composites and with integrated or low cost tooling are of great importance. In addition, payload envelope size constraints of launch vehicles must be overcome for future missions. So inflatable habitats and expandable structures that allow for a deployed structure to meet mission requirements, for example sufficient habitable volume for crewed missions, or a very large and/or precise surface for in-space collectors or reflectors, while fitting within the launch payload geometry constraints are important technology needs.

Benefits of Technology

The benefits of technologies to future missions are increased payload to orbit, and space systems that can be much larger and/or have lower mass, higher precision and/or higher reliability than state of the art systems.

Table 9. TA 12.2.1 Technology Candidates – not in priority order

TA	Technology Name	Description
12.2.1.1	Out-of-Autoclave Primary Structure	Design and economic fabrication of large structure without autoclave pressure that is useful for both large components and for bonding of assemblies outside an autoclave.
12.2.1.2	Composite Cryogenic Tank	Large composite cryogenic tank for launch vehicles and in-space propellant depots.
12.2.1.3	Composite and Inflatable Habitat	PMCs and inflatable habitat.
12.2.1.4	Very Large Solar Array Structure	100 to 1,000 kW class solar array structure.
12.2.1.5	Precision, Expandable Structure	Precision, expandable structure.
12.2.1.6	Lander and Surface Habitat	Lightweight lander and surface habitat.

TA 12.2.2 Design and Certification Methods

Design and certification methods are necessary for development of any structural system. The present development approach to design and certify a structure is based on a "building block" sequence of structural components from very small material coupon scales to large, full scale assemblies or components. The structural response and failure modes are interrogated at each scale to provide a statistically significant dataset for design and certification. This is a highly empirical, heritage approach from aircraft design. However, from a time or economic point of view, it is not well suited to space hardware requiring only a few replicate production runs.

Technical Capability Objectives and Challenges

Design and certification methods are necessary for development of any structural system. Heritage design methods will, in general, not be applicable to new structural technologies or even to existing technologies used in radically different applications, for example, composite structures developed for aircraft used in a space application. Current design and certification practices are not able to quantify appropriate factors of safety or design the robust tests and models needed to introduce new lightweight materials and efficient structural designs. A series of products could be developed that provide progressively greater capabilities in the ability to design and certify structures using a model-based approach; the emphasis here is to strip away unneeded margin(s) in weight and cost by using newly developed physics-based understanding, advanced predictive models, to quantify and maintain extreme reliability. The coupling of the design and analysis to loads is implicit in these efforts. A balanced mixture of developing high-fidelity analytical tools, failure prediction capabilities from both deterministic and probabilistic standpoints, and validation of the tools with test data is essential to creating a model-based design, development, test, and evaluation process that can be used with confidence. The "Virtual Digital Certification" capability for structures thus derived will provide a new paradigm for developing and qualifying safe structures especially those using new materials designs with little heritage experience, which may be complicated by multifunctional capabilities – without undue conservatism that causes mass penalties, and in a systematic and cost-effective manner. In addition, this capability provides a strong foundation for the "Virtual Digital Fleet Leader."

Benefits of Technology

The benefits of technologies to future missions are reduced cost and time to develop and certify flight systems and higher confidence in the safety and reliability of the systems fielded.

Table 10. TA 12.2.2 Technology Candidates – not in priority order

TA	Technology Name	Description
12.2.2.1	Streamlined Design Analysis Cycle (DAC) Process	Streamlined and integrated analysis tool and process
12.2.2.2	Method for Composite Allowable Prediction	Improved methodology for composite design allowables.
12.2.2.3	Probabilistic Design Methodology	Probabilistic methodology for structural design and certification.
12.2.2.4	High-Fidelity Response Simulation	Fidelity of structural analysis tools.
12.2.2.5	Virtual Digital Certification Method	Analysis-based certification of structures.
12.2.2.6	Landing Dynamics Prediction Method	Integrated analysis and design methodology for landing dynamics.
12.2.2.7	Virtual Digital Fleet Leader Certification Methods	Integrated analysis, design, and structure sustainment methodology.

TA 12.2.3 Reliability and Sustainment

State of the art for structural reliability is based upon a heritage experience from deterministic practice. NASA analysis to a three standard deviation level of environment severity and a 90 to 95 percent material capability, protected by an approximately 1.4 to 2.0 factor of safety, has resulted in an accepted level of vehicle mission success regarding aircraft and spacecraft structure. However, beyond the generally accepted heritage experience, the reliability of the primary structure is not clearly defined. The ability to predict the mission life based upon actual in-flight environments is better for some materials and structures than others; but not sufficient for the tight structural margins needed for future deep space exploration. Also, the effect of a trim primary structural reliability upon the systems that it supports is not clearly understood in terms of all potential failure mechanisms. Much of the stochastic methodologies have been theoretically developed, but not to a production state of implementation.

Technical Capability Objectives and Challenges

Advancement in reliability and sustainment methods are needed to ensure that structures are developed to be reliable and safe, and that these levels of reliability and safety can be maintained throughout the service life of the system. This requires the development and inclusion of statistically based designs and methods for dependable determination of the participation of structural reliability into the overall flight vehicle reliability concomitant with the needed autonomy for deep space missions.

New lightweight materials and multifunctional structural designs have very different characteristics than the experience base, requiring new understandings of mechanisms for damage initiation, damage propagation and structural degradation, monitoring methods to detect and diagnose damage, and repair methodologies to restore structural integrity.

Deep space missions change the paradigm of depot-based sustainment as used for aircraft and the Space Shuttle, or of specially planned resupply and repair missions that are possible with a near-Earth space station. Thus, sustainment must depend on understanding the mechanics of damage and degradation so that extreme reliability can be designed into the structure; health monitoring that is used to detect damage and integrated with diagnostic and prognostic methods to characterize the damage and the structural residual life; and operational approaches to adjusting mission parameters to extend life or to effect a repair, or a self-repair, in the most effective manner. The integration of these technologies into the Virtual Digital Fleet Leader is the culmination of this reliability and sustainment capability.

Autonomous inflight mitigation strategies address the need for deep space mission support where a robust, adaptive design of the vehicle itself will have to accommodate changing environments that may not have been foreseen in the initial design. Current design and operational experience cannot be seen as the pattern for interplanetary spacecraft when logistical support from a nearby planet or Shuttle is no longer available. Contributing technologies such as efficient health monitoring, adaptive structures, and self-healing materials must be incorporated into autonomous operational and repair strategies for deep space missions.

Benefits of Technology

Technology benefits include the physic-based ability to better understand the structure, on a system basis, for efficiency (lighter-weight, more robust, increased autonomy), the establishment of a foundation for autonomy in deep space sustainment, and the ability to develop a structural reliability that can be integrated into a full vehicle reliability throughout a mission.

Table 11. TA 12.2.3 Technology Candidates – not in priority order

TA	Technology Name	Description
12.2.3.1	Predictive Damage Method	Experimental method of damage progression for modeling predictive design allowables, accurate simulation of damage initiation and propagation with significantly reduced testing schedule and cost.
12.2.3.2	Life-Extension Prediction Method	Capability to model the integrity of a structure at any time in its life to assess the remaining life based upon the actual flight history (beyond the design environment).
12.2.3.3	Structural Health Monitoring and Thermal Health Monitoring (SHM/THM) System Integration	Data acquisition system with distributed sensors to report environmental and structural integrity information.
12.2.3.4	In-Situ Structural/Thermal Assessment Model	Integrated mathematical modeling capability to interpret the structural and thermal sensor output.
12.2.3.5	Autonomous In-Situ Structural/Thermal Repair System	Integrated capability to interpret structural anomalies and effect repairs.
12.2.3.6	Virtual Digital Fleet Leader Sustainment	Integrated high-fidelity certification models, service life inspection and health monitoring assessment data, and life extension prediction methods with test tools and methods.

TA 12.2.4 Test Tools and Methods

State of the art for test tools and methods is to create a model, instrument a version of the hardware, perform a test on the ground by some encompassing load, thermal, mechanical, or other, applied to simulate flight as well as possible, and correlate the model to the test. Flight tests are somewhat separate and are often called demonstration tests since they are at near nominal flight conditions. The objective for deep space is to incorporate the test tools such as non-contact scanning and structural and health monitoring systems, into the digital package for design, analysis, and manufacturing so that models are the leading certification product; and can be adapted and updated based upon actual mission environments throughout the life cycle.

Technical Capability Objectives and Challenges

Integrated flight test data identification and usage means an integrated package of hardware and software which would allow high-fidelity model correlation at the vehicle level to better understand vehicle response to flight environments, including system damping and modal performance; and then to better incorporate this information into the vehicle certification process, a benefit in terms of cost and schedule. Full-field, non-contact, data acquisition systems include point and global measurements and allow direct interface to the design and analysis models. This capability will reduce test set-up and data post-processing time from days to hours while providing a higher fidelity model correlation capability. Full-field model verification and validation can be incorporated with component and flight test data to improve the vehicle certification process. This provides both quantitative and qualitative model correlation at a vehicle system-wide level and enables virtual digital certification, and better understanding of structural response enables distributed health monitoring and response control. A model of a water landing, where analytical instrumentation is available on a full-field basis to correlate with full-field test tools for a more complete analytical correlation can enable higher fidelity loads and structural math models, active structural control, and adaptive structural design, as well as a more efficient certification process.

Improved test tools, such as laser scanning, vision based, infrared, wireless, and power scavenging sensors, provide new capabilities that better couple with computer-based analytical tools and offer new opportunities for test and model correlation and structural certification by analysis including: a) lower cost and shorter schedule in the qualification phase, b) higher fidelity correlation and better understanding of structural response, c) lighter-weight and less intrusive to the vehicle design and operation, and d) better life and repair capability during the sustainment phase.

Test validation of loads models is historically performed to predicted design loads that are loosely correlated to flight test and wind tunnel data, design to loads meet or exceed the measured loads. However, wind tunnel tests are conducted under static conditions, and do not accurately capture transient events, such as accelerating flight. This is particularly true for buffet, aeroacoustic, and aeroelastic testing where models tested at steady conditions have the opportunity to build up a full response to an environment that may only exist for a short period of time during flight. Vehicles designed to loads derived from these steady conditions can be over conservative in their development. The more precise integration of flight test and in service will allow for a more precise design, less uncertainty means more confidence in the loads models, and less mass in the design.

Benefits of Technology

Technology benefits include a more physics-based understanding to incorporate flight test mean conditions into the certification process; reduction in the certification cost and schedule for new vehicle development; and potentially a new development and certification paradigm that mixes design, analysis, prototype fabrication, and test and evaluation in an optimized development spiral. Integration of advanced analytical tools and sensory systems to advance certification, reliability, and sustainment will also enable the critically needed robustness and autonomy for deep space exploration.

Table 12. TA 12.2.4 Technology Candidates – not in priority order

TA	Technology Name	Description
12.2.4.1	Integrated Flight Test Data Identification Model	Analytical model correlation of flight data for model certification and structural certification.
12.2.4.2	Full-Field Data Acquisition System	Far field and integral structural sensor systems for point and global measurements.
12.2.4.3	Full-Field Model Verification and Validation Model and System	Testing and correlation capability to enable verification and validation for full scale, full field analytical models, test hardware, instrumentation, data acquisition, and data reduction.
12.2.4.4	Virtual Digital Certification Method and System	Precursor to the Virtual Digital Fleet Leader capability; tests methods for correlation across the building block spectrum, engaging the available structural health monitoring and thermal health monitoring capabilities to address the full life cycle of a space vehicle.
12.2.4.5	Virtual Digital Fleet Leader Testing	This represents the testing and model correlation portion of the virtual fleet leader to better understand vehicle life in the design phase for real time adjustment to the vehicle life during its mission.

TA 12.2.5 Innovative, Multifunctional Concepts

Heritage vehicles have mostly involved discrete designs where functionality is provided in separate subsystems such as shielding, electronics, sensors, which are added onto, instead of incorporated into, vehicle structure. The state of the art for integrating these subsystems is at a low Technology Readiness Level (TRL). The objective is to develop materials and processes and design technologies to integrate subsystems into vehicle structures, and mass and volume reduction that is critical for deep space travel.

Technical Capability Objectives and Challenges

Future high performance structural concepts for deep space missions, as well as near-Earth orbit missions can be transformative with multifunctional structure capabilities. These capabilities can include both pressurized and unpressurized structures. A special pressurized structure is a multifunctional cyrotank, integrating insulation in the structural design. Other multifunctional structures with integrated capabilities may include reconfigurable structures, adaptive structures, and structures with active and passive capabilities as well as those with integrated windows.

Multifunctional structure families for both pressurized and unpressurized components provide a mix of micro-meteoroid orbital debris, radiation, electrical sensor and harness, and thermal controls embedded therein resulting in a high level of system integration and autonomy while reducing mass and volume. Pressurized structures will incorporate permeability protection and leak mitigation while unpressurized variants do not. Cryotanks that provide integrated insulations and habitation structures with integrated window design capability are also highly important capabilities. Demonstration by 2022 of these innovative structural approaches will help achieve Mars exploration goals with crewed and uncrewed structures.

A second form of multifunctional structure is reusable modular structures. These provide modular component designs to be used in multiple mission systems. This will reduce development time and cost and change the paradigm of developing mission concept hardware development from "one unit, one purpose" into a new way of thinking where "one unit, one design" can be reconfigured or repurposed to be used multiple places within a mission and across many missions. Demonstrated by 2021 the "one unit, one design" paradigm allows for robotic missions at greatly reduced cost and schedule.

A third form of multifunctional structures is one that changes performance for varying flight conditions. "Active control of structural response" provides response changes through active sensing and manipulation of structural elements, and "integrated adaptive structures" is the next step where the changes in response occur autonomously. Both capabilities enhance structural design flexibility, performance, and safety throughout their flight environments while reducing system mass. These capabilities need to be demonstrated in 10 years to be available for future science missions envisioned to suppress vibration loads for more precise imaging.

Benefits of Technology

Multifunctional structures can be optimized to integrate subsystem functionality to reduce mass and/or volume, or can focus on modularity to reduce integration time to provide reduced costs and schedule. Currently subsystems, for example, thermal and mechanical subsystems, work independently and require a systems engineer to bridge requirements where performance, interfaces, and implementation interfere. When integration of functionality is considered, it pre-addresses interface design by reducing the number of interfaces, thereby reducing the engineering effort. This results in reduced integration time and cost. Additionally, performance improvements not formerly considered, such as load suppression, can be implemented with no or little mass and volume impact. Multifunctional structures technology can change designs used to reach deep space safely, change how environments are mitigated, and improve space science structure performance.

Table 13. TA 12.2.5 Technology Candidates – not in priority order

TA	Technology Name	Description
12.2.5.1	Multifunctional Cryo-Tank	Cryo-tanks designs based on integrated insulation, structural, and sensor elements.
12.2.5.2	Multifunctional Pressurized Structure	Pressurized structure designs with integrated micro-meteoroid orbital debris, radiation, and permeability protection, electrical harnessing, thermal control, and sensor subsystems.
12.2.5.3	Multifunctional Non-Pressurized Structure	Non-pressurized structure designs with integrated micro-meteoroid orbital debris and radiation protection, thermal control capability, electrical harnessing, and sensor subsystems.
12.2.5.4	Reusable Modular Component	Structure design with components for multiple purposes and multiple uses.
12.2.5.5	Integrated Window	Provide integrated window and structure design that enables proper sealing, strength, and reparability for space application.
12.2.5.6	Active Control of Structural Response Model	Structure designs with active controls to optimize structure performance.
12.2.5.7	Integrated Adaptive	Structure designs with inherent capability to change mechanical and functional performance in-flight.

TA 12.2.6 Loads and Environments

The current technology includes both deterministic and stochastic methodologies to understand and provide applied loads for vehicle development. However, notable improvements are needed for incorporation of the environmental loading into the structural and system capabilities for future missions beyond low-Earth and lunar orbits.

Technical Capability Objectives and Challenges

Loads and environments are developed for every designed component on a spacecraft or aircraft. This is a crosscutting discipline that includes contributions for aero, thermal, structural, mechanical, and chemical environments. Current technology offers room for improvement in the development and assimilation of mechanical (static and dynamic) and non-mechanical (radiation, atomic oxygen, differential thermal) environments into the structural and system capabilities for future missions beyond low-Earth and lunar orbits.

Combined environments refer to the synergized effects of environmental loading. For example, aerodynamic pressures, both quasi-steady state and transient; acceleration; vibration; temperature; radiation; and others act simultaneously and in varying proportions upon the structure and components of a spacecraft. Currently, these are often developed in a worst on worst fashion, tested separately, and combined analytically. More efficient integration into the design and analysis cycles, along with attention to the purposeful design for multi-functionality, and the incorporation of active sensory system response, will provide more precise models in a timely design and certification process. Improved methods for accurate mathematical representations of local and global loads and environments are required for a more precise design, accommodation for less uncertainties, and thus enable structural mass savings with a better quantified reliability. Improved statistical quantification of environmental uncertainties is an integral step in structural reliability assessment with lower mass. New dynamic analysis and ground and flight test techniques are required to accurately represent transient systems such as changing mass, stiffness, and dynamic pressure, during flight. New aero-structural, vibro-acoustic, and shock response prediction technologies are also needed. Physics-based methods to predict aero-acoustic and buffet environments are required to replace the empirical techniques, presently employed throughout the industry, and to supplement and focus costly testing. Fully coupled environmental and structural models should be developed to reduce reliance on approximate load distribution and allocation techniques, which can unnecessarily penalize the structural design. Accurate prediction of nonlinear effects is essential to further reduce conservatisms. Buffet, aero-acoustic, protuberance air-load, and aero-elastic-effect prediction would each benefit from development of these coupled technologies. These improvements will allow for more exact design and for more critical structural response control.

Mission loads and environments monitoring refers to in-situ monitoring of static, dynamic, thermal, and aero environments, both nominal and off-nominal, throughout the system service life. Conceptually, an automated evaluation tool will locate, quantify, and track operational degradation as it occurs using this data. The result is reduced cost and impact of mission inspections, a more precise residual life assessment, and an opportunity to refine analytical tools for the remainder of the mission and for future missions.

Benefits of Technology

The primary benefit of defining loads and environments is improved structural and system efficiency from a better physics-based understanding of the constituent loads and their integration into the system. This provides reduction of uncertainty in the applied loads. Uncertainties are typically addressed by adding capability, usually in the form of additional structural and/or system mass.

Table 14. TA 12.2.6 Technology Candidates – not in priority order

TA	Technology Name	Description
12.2.6.1	Combined Environments Modeling Tool	Tool that integrates the environmental loading of a structure to reduce uncertainties in the interactions.
12.2.6.2	Improved Method for Accurate Local and Global Loads and Environments	Method that reduces the environmental loading of a structure to the local load of a structural part (primary or secondary) to reduce uncertainties in process.
12.2.6.3	Test Validation Model	Model and test correlation of multiple, competing, and transient load environments for aerovehicles, launch vehicles, and planetary descent vehicles.
12.2.6.4	Design for Monitoring Strategy	Structural monitoring strategy that enables more efficient design, including certification updates during a mission, autonomous assessment, and repair.
12.2.6.5	Mission Loads and Environments Monitoring	In-flight loads monitoring that enables the transition from design loads to actual mission loads and exact local structural response. Structural life assessment based upon flight history and updated predictions. Reliable measurement and acquisition of surface fluctuating pressures and corresponding structural responses on large scale flight vehicles (also applicable to wind tunnel models).
12.2.6.6	Autonomous In-Flight Mitigation Strategy	Strategies that enable real-time adjustments within a structural system to mitigate structural anomalies various mission phases based upon flight history and updated predictions. Strategies may apply to static and dynamic structural loads to mitigate failure, fatigue, and/or control-structures interactions; or they may apply to mitigation of structural vibration and interior acoustic load (for example, during launch and ascent) using efficient adaptive and active technologies.

TA 12.3: Mechanical Systems

Mechanical Systems consists of six capabilities: deployables, docking, and interfaces; mechanism life extension systems; electro-mechanical, mechanical, and micromechanisms; design and analysis tools and methods; reliability, life assessment, and health monitoring; and certification methods. Mechanism technologies primarily overcome physical limitations due to launch vehicle constraints and extending mechanism life in harsher environments such as regolith and cryogenic. Deployable methods, especially for precision large rigid structures or flexible materials are the enabling force behind developing the larger systems needed to attain advancements in science and engineering of today and tomorrow. In addition, micro-mechanisms foster a safer environment for our missions to land and explore new worlds. Exciting systems that keep NASA's finger on the pulse of each vehicle are the stepping-stones of an interrelated correlated analysis system, digital certification, and the Virtual Digital Fleet Leader.

Sub-Goals

Mission requirements placed on mechanisms will continue to become more demanding as robotic and human space missions push farther into deep space. To support those demands, NASA needs to develop robust, long-lived mechanisms capable of performing in the harsh environments encountered.

Table 15. Summary of Level 12.3 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
12.0 Materials, Structures, Mechanical Systems, and Manufacturing	Goals:	Develop materials to increase multi-functionality and reduce mass and cost (radiation protection and mass reduction challenges). Provide innovative designs and tools for robustness and superior structural integrity for deep space and science missions (reliability and mass reduction challenges). Design and develop robust, long-life mechanisms capable of performing in the harsh environments (reliability challenge). Advance new processes and model-based manufacturing capabilities for more affordable and higher performance products (mass reduction/affordability challenge).
Level 2		
12.3 Mechanical Systems	Sub-Goals:	Improve life and reliability of mechanisms to extend the life of space missions. Improve the precision alignment capability of mechanisms to extend the capability of deployable structures.
Level 3		
12.3.1 Deployables, Docking, and Interfaces	Objectives:	Overcome the constraints of launch vehicle fairing size; combine and/or separate spacecraft and spacecraft systems either remotely or with humans in the loop; and develop interfaces that will cost effectively and more reliably streamline system and spacecraft connectivity.
	Challenges:	Common universal interchangeable interfaces approach. Extensible structure deployment.
	Benefits:	Provides cost savings for larger deployed structures by overcoming launch vehicle payload constraints, enabling mission design flexibility for unique interfaces, allowing late supplier changes without extensive redesign, interfacing between a wide variety of spacecraft, and providing a low shock and highly reliable means of restraints and releases.

Table 15. Summary of Level 12.3 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
12.3.2 Mechanism Life Extension Systems	Objectives:	Extend the life of mechanisms operating in harsh environments.
	Challenges:	Operational environments with extremes of temperature, pressure, radiation, dust, micrometeoroid impact, and shock.
	Benefits:	Overcomes the current life limitations of mechanical components and moving mechanical assemblies operating in harsh conditions, such as dusty and cryogenic environments. Affords more reliable operation and longer mission duration. Provides reliable, low-temperature science acquisition associated with deep space and planetary probe missions.
12.3.3 Electro-Mechanical, Mechanical, and Micromechanisms	Objectives:	Complete the development and testing of tools and interfaces and fluid transfer allowing increased complexity of tasks.
	Challenges:	Number and complexity of systems. Withstand deep thermal cycles, thermal mismatches, misalignment tolerances, and seal integrity for cryogenic fluid transfer.
	Benefits:	Provides in-situ buildup and repair of deep space missions, servicing of low-Earth orbit (LEO) satellites, and resupply to storage depot.
12.3.4 Design and Analysis Tools and Methods	Objectives:	Combine numerical analysis methods of different disciplines to enable creation of a single model of spacecraft mechanical systems, reducing overall stack-up of margins.
	Challenges:	Coordinated motion, force control across the entire system, and fusion of localization with force control.
	Benefits:	Allows for real time assessment of mechanism performance, improving ability to simulate and evaluate multiple variables and affording an interrelated and correlated system, eventually leading to the ability to monitor the health of systems. Reduces stack-up margins across multiple disciplines.
12.3.5 Reliability, Life Assessment, and Health Monitoring	Objectives:	Timely anomaly detection, prognosis, and life assessment prediction for vehicles or mechanical systems.
	Challenges:	Accurate determination of cumulative damage. Integration of systems.
	Benefits:	Provides more accurate model correlation and better predictive modeling. Provides predictive damage methods that allow more efficient configurations and reduced reliance on testing.
12.3.6 Certification Methods	Objectives:	Model complex or integrated system failure modes with high confidence.
	Challenges:	Deployable system size and gravity.
	Benefits:	Provides better, test-correlated models and test-verified physics, thereby reducing cost and schedule by predicting failures well in advance of building and life testing the hardware. Reduces costs associated with multiple design iterations and allows for optimum design without the need for expensive test programs. Allows the future of digital certification.

TA 12.3.1 Deployables, Docking, and Interfaces

NASA and commercial partners are working to improve docking load attenuation systems for beyond LEO missions and environments. The main objective is interface commonality while reducing mass and costs. The associated issues are repeatability and predictability of stowing and deploying large structures from a small launch package to very high tolerances.

Technical Capability Objectives and Challenges

This technology area is comprised of capabilities that will allow NASA to overcome the constraints of launch vehicle fairing size; to combine and/or separate spacecraft and spacecraft systems either remotely or with humans in the loop; and develop interfaces that will cost effectively and more reliably streamline system and spacecraft connectivity. Table 16 expands these three categories into more specific key technologies and associated challenges including common universal interchangeable interfaces and highly reliable yet fully verifiable restraint and release devices that will revolutionize capabilities to deploy, dock, and separate systems of all scales. Additionally, high-payoff extensibility is explored in the areas of deployment of flexible materials, large lightweight stiff structures, mechanisms for auto precision landing and hazard avoidance, and precision structural deployment mechanisms. The precision structural deployment mechanisms technology is game changing, as achieving extremely tight tolerance reaps huge benefits for science. The challenge of these technologies is deploying large combinations of flexible and lightweight stiff mechanical systems with precise and repeatable results, thereby overcoming the limits of launch vehicle fairing geometry.

Benefits of Technology

Deployables, docking, and interface technology development will lead to cost savings for larger deployed structures through overcoming launch vehicle payload constraints, enabling mission design flexibility for unique interfaces, allowing late supplier changes without extensive redesign, permitting interfaces between a wide variety of spacecraft, and providing a low shock and highly reliable means of restraint and release of interfaces.

Table 16. TA 12.3.1 Technology Candidates – not in priority order

TA	Technology Name	Description
12.3.1.1	Common Universal Interchangeable Interface	Interface that will cost effectively and more reliably streamline system and spacecraft connectivity.
12.3.1.2	Low Shock Release Device	Verifiable, resettable, fast acting release device that reduces shock vibration.
12.3.1.3	Deployment of Flex Material	Mechanism that can reliably deploy a wide variety of structural members.
12.3.1.4	Large Lightweight Stiff Deployable Packaging Technique	Packaging technique for large lightweight rigid deployable structures.
12.3.1.5	Mechanism for Auto Precision Landing Hazard Avoidance	Real-time response to landing hazards.
12.3.1.6	Precision Structure Deploy Mechanism	Design of high precision hinge and latch for large structure.

TA 12.3.2 Mechanism Life Extension Systems

Mechanism life extension involves the limitations of mechanism life in extreme and harsh environments. Overcoming the life-limiting properties of current lubrication and components in harsh environments of dust and cryogenics is the main objective.

Technical Capability Objectives and Challenges

Since many future goals demand long-duration missions, safety and reliability are the key targets of this mechanical systems technology. Extra challenging is the fact that most future missions involve operational environments with extremes of temperature, pressure, radiation, dust, micrometeoroid impact, and shock. Lengthening mission life and developing systems with ample margin opens the gateway to achieving farther-reaching goals much faster.

Benefits of Technology

Development of long-life bearing and lubrication systems will overcome the current life limitations of mechanical components and moving mechanical assemblies operating in harsh conditions such as dusty and cryogenic environments, and will afford more reliable operation and longer mission duration. Cryogenic long-life actuators will enable reliable low temp science acquisition associated with deep space and planetary probe missions.

Table 17. TA 12.3.2 Technology Candidates – not in priority order

TA	Technology Name	Description
12.3.2.1	Long-Life Bearing/Lube System	Improve bearing performance and life through advanced design, materials, lubricants, and relubrication system.
12.3.2.2	Cryo Long-Life Actuator	Provide long-life actuator for cryogenic valves and couplings that operates in long-duration vacuum conditions with deep thermal cycles.

TA 12.3.3 Electro-mechanical, Mechanical, and Micromechanisms

Mechanical robotic tools and cryogenic fluid transfer actuators have been developed but not widely used. Robotic tool issues include complexity and the number of systems required for the wide array of tools and systems needed by NASA missions. Cryogenic fluid transfer challenges are to design robustness to withstand deep thermal cycles, thermal mismatches, misalignment tolerances, and seal integrity challenges while providing mission-critical functions. Reproducing and combining required environments to create comprehensive tests leading to analytical tool validation will bring these technologies to flight readiness much faster than current methods.

Technical Capability Objectives and Challenges

This technology area encompasses the full array of mechanisms, micro, small, and large. Milestones include robotic assembly tools and interfaces that will allow robotic assembly, manipulation, and servicing of spacecraft and spacecraft components; cryogenic and fluid transfer technologies that ensure that critical fluids can be transferred from a carrier, resupply vehicle to a storage depot, habitable space station, or exploration vehicle for storage or eventual use in long-term space missions; and active landing attenuation systems that provide efficient mechanisms to soften the impact load for landing systems on Earth, other planets, or near-Earth asteroids, and potentially reduce system weight by eliminating other heavier passive attenuation systems.

Benefits of Technology

These technologies have wide-ranging benefits for in-situ build up and repair of deep space missions, servicing of LEO satellites, and resupplying storage depots and long-term space missions.

Table 18. TA 12.3.3 Technology Candidates – not in priority order

TA	Technology Name	Description
12.3.3.1	Robotic Assembly Tools/Interfaces	Tools for robotic assets to cut, grasp, and turn for assembly and maintenance of structures.
12.3.3.2	Cryogenic and Fluid Transfer	Automated fluid coupling design that operates under cryogenic conditions in space.

TA 12.3.4 Design and Analysis Tools and Methods

Analysis tools are widely used but the results must be correlated to test data for verification and flight certification. Using evolutionary algorithms for solving multi-objective problems is not currently employed for flight hardware.

Technical Capability Objectives and Challenges

This technology area contains the critical items and techniques needed to design and analyze any and all mechanical systems technologies. These analysis tools and methods combine numerical analysis methods of different disciplines to enable creation of a single model of spacecraft mechanical systems in lieu of multiple iterative cycles of serial analyses. This holistic approach would allow for the reduction of overall stack-up of margins across disciplines, for example, aero loads, vehicle dynamics, structural response; and efficient vehicle and component diagnosis, prognosis, and performance assessment when implemented with a health management system.

Challenges include coordinated motion, force control across the entire system, and fusion of localization with force control.

Benefits of Technology

Access to high data rates across systems will allow for real-time assessment of mechanism performance, improving the ability to simulate and evaluate multiple variables. This creates an interrelated and correlated method for monitoring the health of systems. Health monitoring will allow for a reduction of stack-up margins across multiple disciplines.

Table 19. TA 12.3.4 Technology Candidates – not in priority order

TA	Technology Name	Description
12.3.4.1	Interrelated Correlated Analysis System	Using evolutionary algorithms for solving multi-objective problems.

TA 12.3.5 Reliability, Life Assessment, and Health Monitoring

This is the process and set of technologies that will ensure the system will perform as required.

Technical Capability Objectives and Challenges

Advances in accurately correlating vehicle or mechanical system life assessment predictions, through the use of health monitoring, is a key to fulfilling mission goals. These technologies ensure vehicles meet reliability and safety requirements relative to the mission and remain within cost requirements.

Leading objectives are timely anomaly detection and prognosis; life extension prediction for mechanical systems which uses cumulative damage from the actual environment to allow for life extension when environments are less extreme than the design case; standard integrated systems for health-monitoring of all systems and sub-systems including power and data.

For this technology area the application of sensors in spacecraft will provide data on the health and reaction of mechanical systems in their service environment, for example, launch, on-orbit, and launch site. The sensor data can be used to create a fully digital representation of the spacecraft. This digital representation provides not only diagnostic, what has occurred to the spacecraft, but also prognostic capabilities to predict how a spacecraft will behave in its next maneuver. Exploration of changing and unknown environments will be much easier to handle for future spacecraft if forward, predictive tools are established.

Benefits of Technology

This technology area will provide more accurate model correlation and better predictive modeling. Enhanced predictive modeling tools result in more efficient configurations and reduced reliance on testing. Sensing actual loads and other parameters will be like having your finger on the pulse of the system.

Table 20. TA 12.3.5 Technology Candidates – not in priority order

TA	Technology Name	Description
12.3.5.1	Predictive Damage Method	Damage prediction using experimental and numerical methods.
12.3.5.2	Embedded System	Sensors embedded in the mechanisms.
12.3.5.3	Life Extension Prediction Method	Methods and procedures for predicting remaining life of mechanisms.
12.3.5.4	Integrated Health Monitoring System	Integrating all health monitoring systems.

TA 12.3.6 Certification Methods

Certification methods can streamline the testing and verification and validation, processes, which are currently an extensive combination of test and analyses, including life testing, which often drive project schedules and cost.


Structures testing for the shell buckling

Technical Capability Objectives and Challenges

Challenges such as deployable system size and gravity inhibit the ability to fully test many large deployable systems. In order to have a complete digital system, subsystems must be certified in cyberspace. This is envisioned through the use of hardware health monitoring and telemetry systems that can help to correlate mechanism performance models. As predictive models improve, the cost of large deployable or other mechanical systems testing may be eliminated.

Benefits of Technology

Improved kinematic and bearing analysis tools will lead to better test correlated models and test verified physics, reducing cost and schedule by predicting failures well in advance of building and life testing the hardware. Test-verified physics leading to probabilistic design will reduce the costs associated with multiple design iterations and allow for optimum design without the need for expensive test programs and enabling the future of digital certification.

Table 21. TA 12.3.6 Technology Candidates – not in priority order

TA	Technology Name	Description
12.3.6.1	Verified Physics Modeling Tool	Analytical modeling of complex integrated system failure modes.
12.3.6.2	Virtual Probabilistic Design Model	Virtual evaluation of design based on failure modes (statistical methods).
12.3.6.3	Digital Certification Method in Cyberspace	Virtual incorporation of test verified physics, and probabilistic design.
12.3.6.4	Virtual Digital Fleet Leader System Certification	The digital representation of the flight system with comprehensive diagnostic and prognostic capabilities to enable efficient development and certification as well as safe, autonomous operation throughout the service life of system.

TA 12.4: Manufacturing

This technology area seeks to identify the next generation of advanced manufacturing technologies that will have the greatest impact on the cost, schedule, and performance for NASA missions.

Advanced manufacturing technology is critical to NASA missions such as the Space Launch System (SLS), the Orion crew vehicle, commercial crew and commercial cargo programs, and science missions. Rapidly advancing manufacturing technologies in areas such as additive manufacturing, composites, modern metals, smart factories, and cyber physical systems can produce dramatic new and superior capabilities for NASA missions.

3D printer headed for the International Space Station

Aerospace structures have challenging requirements for reliability, which in turn place demands on the ability to carefully control the production of the materials to enable optimized, predictable manufacturing performance. The design of new material systems requires years of expensive testing and development in order to transition to manufacturing. These requirements, coupled with a hyper-competitive marketplace for aerospace, are driving industry to develop high-production efficiency technologies.

Advanced manufacturing is comprised of a family of activities that depend on the use and coordination of information, automation, computation, software, sensing, and networking, and make use of cutting-edge materials and emerging capabilities enabled by the physical and biological sciences, for example nanotechnology, chemistry, and biology. It involves both new ways to manufacture existing products, and the manufacture of new products emerging from new materials or advanced technologies.

Sub-Goals

This technology area is focused on emerging technologies that have the potential to significantly improve existing manufacturing methods or processes and lead to entirely new and revolutionary processes to enable production of aerospace products. Ultimately, realized improvements will include more rapid production, increased accuracy, defect reduction, reduced costs, more efficient utilization of resources, and reduced environmental impact. The emphasis will be to develop more affordable, automated and integrated manufacturing of components and structures and the verification of those processes through experimental testing.

Table 22. Summary of Level 12.4 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
12.0 Materials, Structures, Mechanical Systems, and Manufacturing	Goals:	Develop materials to increase multi-functionality and reduce mass and cost (radiation protection and mass reduction challenges). Provide innovative designs and tools for robustness and superior structural integrity for deep space and science missions (reliability and mass reduction challenges). Design and develop robust, long-life mechanisms capable of performing in the harsh environments (reliability challenge). Advance new processes and model-based manufacturing capabilities for more affordable and higher performance products (mass reduction/affordability challenge).
Level 2		
12.4 Manufacturing	Sub-Goals:	Develop innovative physical manufacturing processes combined with the 'digital thread' that integrates modern design and manufacturing.

Table 22. Summary of Level 12.4 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
12.4.1 Manufacturing Processes	Objectives:	Achieve rapid production, reduced cost, increased accuracy, and defect reduction.
	Challenges:	New materials and design databases. New processes and scale-up of processes.
	Benefits:	Provides affordable capability performance needed to deliver products. Reduces cost and risk on commercializing new technologies.
12.4.2 Intelligent Integrated Manufacturing and Cyber Physical Systems	Objectives:	Implement the “digital thread” model-based manufacturing environment.
	Challenges:	Physics-based modeling, simulation, and sensory control. Integrated engineering tools.
	Benefits:	Reduces cost and time to develop and certify flight systems and innovative methodologies and practices for supply chain integration.
12.4.3 Electronics and Optics Manufacturing Process	Objectives:	Develop electrical components for extreme environments and precision optics component manufacturing.
	Challenges:	Understand and improve on commercial models and processes. Processes for optical quality on lower mass components.
	Benefits:	Reduces optical system mass and improves optical performance. Provides larger optical systems with precision exceeding current capability. Provides spacecraft with a lower mass for equivalent power generation using improved solar array cells. Allows for mission extension through harsh environments for longer, more reliable, and safer mission execution.
12.4.4 Sustainable Manufacturing	Objectives:	Reduce or eliminate the use of hazardous materials in production processes.
	Challenges:	Identify where environmental impact is the largest, allowing for targeted reduction in waste, toxicity, and energy.
	Benefits:	Lowers manufacturing productions costs, leading to economic sustainability.
12.4.5 Nondestructive Evaluation and Sensors	Objectives:	Develop accurate assessment of the as-built state correlated to performance.
	Challenges:	Detecting precursors of unanticipated global degradation, as well as rapidly identifying and locating suddenly occurring mission-threatening damage.
	Benefits:	Advances modeling methodologies that will aid the interpretation of nondestructive evaluation (NDE) responses that inform material performance evaluations. Provides numerical models that accurately simulate the physics of selected NDE energies interacting with the material and manufacturing defects.

TA 12.4.1 Manufacturing Processes

Manufacturing processes turn materials into components and components into products. Manufacturing process innovations such as solid state joining, composite structure processing, and additive manufacturing have enabled the introduction of new, lower cost space components and products for propulsion and spacecraft. Advances in near-net-shape manufacturing technology have demonstrated entirely new methods to fabricate lower cost, lighter-weight, and higher performance metallic structures. The availability of advanced manufacturing processes is a key factor to improving the performance and affordability of many NASA systems.

Technical Capability Objectives and Challenges

Technologies in the area include: innovative metallic processes, polymer matrix composite (PMC) processes, ceramic matrix composite (CMC), and in-space assembly, fabrication, and repair (ISAFR).

Innovative metallic processes including critical, high-value, processes such as solid-state joining and near-net shape forming can enable high-productivity and improved performance in metallic fabrication. Additionally, innovative developments such as maturation of new metals processes and development of traditional processes for new metals like bulk metallic glasses contribute to the viability of the Agency's projects and a domestic aerospace structures manufacturing base. Metallic materials are the prime choice of materials by design engineers due to their reliable and predictable mechanical and design properties. Current manufacturing methods for metallic structure are robust and reliable, but are based on 50 year-old technology that tends to be expensive and material inefficient. Advanced near-net-shape manufacturing methods have demonstrated dramatic improvements in material utilization, reliability, and performance. Technologies that support replacement of multi-piece machined and welded components with single-piece elements have the greatest payoff. The manufacturing flexibility afforded by these methods will open the design space for metallic structures.

Technologies are also needed to provide PMC processes that result in large composite structures with the required performance for space applications. PMC manufacturing technology is crosscutting in many areas and systems, offering improvements for heavy lift vehicles, in-space applications, and fueling depots. The largest contribution is mass savings; however, there could be advantages related to controlling thermal expansion and radiation shielding. Composite components are easily adaptable to changes in design. The development of manufacturing processes for PMC's dovetails closely with efforts to develop new materials.

Friction stir welded aluminum tank section

CMC processes are needed that result in large composite structures with the required performance for space applications. CMC processes and carbon-carbon (C/C) composites have applications for rocket engine nozzles, air-breathing propulsion flow path structures, hot structures such as control surfaces and body flaps, both heavily load bearing, as well as leading edges, lightly load bearing. The technology is still not "off the shelf," with challenges including design databases and manufacturing experience.

ISAFR technologies greatly advance space exploration capability through reduced risk, for example, on-orbit repair capability, reduced mass requirements for spare parts and other materials inventory, and reduced operations via automated deployment or fabrication. ISAFR technologies, such as direct digital manufacturing, make possible devices for replacing parts or building new parts. They also provide a means of automatic construction or repairing entire components or systems that can be used anywhere while in-orbit or at extraterrestrial sites.

Benefits of Technology

Innovative manufacturing processes enable future NASA missions through more affordable and capable performance. This technology area is vital to reducing cost and risk of future missions as well as the cost of commercializing new technologies.

Table 23. TA 12.4.1 Technology Candidates – not in priority order

TA	Technology Name	Description
12.4.1.1	Innovative Metallic Process	Critical, high-value process (for example, solid-state joining, additive manufacturing, near-net shape forming).
12.4.1.2	Polymer Matrix Composite (PMC) Process	PMC process that results in large composite structures that have required performance for space applications.
12.4.1.3	Ceramic Matrix Composite (CMC) Process	CMC process that results in large composite structures that have required performance for space applications.
12.4.1.4	In-Space Assembly, Fabrication and Repair (ISFAR) Process	ISFAR process that results in large composite or metallic structures that have required performance for space applications.

TA 12.4.2 Intelligent Integrated Manufacturing and Cyber Physical Systems

Emerging digital and model-based intelligent integrated manufacturing systems can drive modern design, manufacturing, and product support processes. These systems can be exploited to dramatically lower cost and reduce cycle time. The 'digital thread' concept can be used to capture all materials and manufacturing data to inform the materials development process. These capabilities are the primary solution for dealing with constantly increasing complexity in products and manufacturing enterprises.

Technical Capability Objectives and Challenges

There is a great opportunity in manufacturing R&D based on innovation for digital and model-based intelligent integrated manufacturing systems. As manufacturing advances, it is increasingly relying on digital technologies such as physics-based modeling, simulation, and sensory control. Over the past two decades, incremental improvements in tools for design and manufacturing have produced substantial improvements in productivity and new products. However, today, the majority of design to manufacturing is still an ad hoc and empirical process. Dramatic gains in affordability will only come from accelerating the development of breakthrough technologies to provide the 'digital thread' that integrates modern design and manufacturing, and to develop integrated engineering tools to exploit a models-based approach throughout the product lifecycle. A model-based supply network for sustainable space exploration will require new terrestrial collaborative supply networks and interplanetary supply-chain technology advancement. The overall objective of this effort is to develop an integrated capability for a virtual enterprise extending from raw materials, through a network of suppliers, to the manufacturers and customers. Virtual process conceptualization and operation describes a complete digital manufacturing process built upon mathematically accurate models that drive and support all stages of the product's manufacture. Simulation models linked to visualization environments can enable rapid and accurate evaluation of product and process alternatives, allowing the input of preferences, and real-time feedback.

Intelligent product definition is a complete digital product built upon explicit, timeless, computer-sensible models that drive and support all stages of the product's lifecycle. The models capture the full spatial, behavioral, and process description of the product and represent the authoritative source of accuracy for the product definition. Intelligent product definitions for all materials and manufacturing processes can be integrated into a system model to assess performance across the full product life cycle.

The cyber-physical system is closely related to robotics since it requires precise coordination between the system's computational and physical elements. However, the cyber-physical systems of the future will far exceed those of today in terms of adaptability, autonomy, and functionality. Advances in cyber-physical systems for NASA have potential to transform our ability to live and work in space. Please see TA 4 Robotics and Autonomous Systems for more information on cyber-physical systems.

Model-based operations and control systems integrate factory, process, reliability, and equipment models with a distributed monitoring and control environment to ensure the acceptable operation of the domain be it machine, factory, or enterprise. This technology provides methods, tools, and components for robust and accurate processes, reliability, and equipment modeling systems that respond to product and production requirements and support the design of optimized production systems.

NASA is developing technologies in the area of additive manufacturing, or 3D printing, to produce a myriad of components and hardware from high-performance rocket engine parts to tools for in-space repair. This technology gives designers an almost endless set of new design options and has the potential to revolutionize the way how almost everything is made.

Benefits of Technology

The benefits of technologies to future missions are reduced cost and time to develop and certify flight systems and innovative methodologies and practices for supply chain integration.

Table 24. TA 12.4.2 Technology Candidates – not in priority order

TA	Technology Name	Description
12.4.2.1	Digital and Model-Based Manufacturing	'Digital thread' that integrates modern design, manufacturing, and product support processes.
12.4.2.2	Model-Based Operations	Development and integration of smart sensors, controls, and measurement, analysis, decision, and communication software tools for factory machines.
12.4.2.3	Additive Manufacturing	Additive manufacturing processes for space and in-space.

TA 12.4.3 Electronics and Optics Manufacturing Process

Segmented optics on a dimensionally stable backplane is the state of the art for space borne science instruments. Optics system manufacturing needs the capability to develop materials and manufacturing techniques to build large monolithic optics that are light and yet stiff enough to maintain shape.

Electronics manufacturing will provide higher efficiency for solar cells and develop material and processes for electronics in extreme temperature and radiation environments.

Technical Capability Objectives and Challenges

Special electronics and optical system manufacturing technologies are similar, as their respective technology advancement will enable humans and machines to reach beyond current capabilities. Solar cells with higher efficiency will allow for smaller solar arrays of equivalent power. Electronics in extreme temperature and radiation environments will ensure the safety of humans during transportation and exploration beyond LEO. Lighter-weight optics and optical structures will translate into larger systems with higher precision and lower mass that peer further into the universe.

Solar cell or photovoltaic material and processes will provide for high-efficiency solar cell production. Currently at 29.5 percent, solar cells can reach 35 percent efficiency as the challenges associated with fabrication of new triple junction solar cells grown on Germanium substrates are overcome. This technology allows more mass for the science portion of the mission rather than the spacecraft, which will enable more stable platforms for better science return.

Special electronics manufacturing provides material and manufacturing processes for electronics in extreme temperature and radiation environments. The commercial electronics industry is leading development in most areas of electronics for NASA applications. The challenge is to understand and improve on commercial models and processes to bring about the affordable production of high performing electronics in extreme environments. This will lead to securing electronics capability for a wide range of missions to places like Mars, and the outer planets.

Testing on six of the 18 mirror segments that will form NASA's JWST's primary mirror

Space optical systems need both lightweight optics and optical support structures. Optical fabrication technology advancement provides optics substrate materials, fabrication processes, and verification metrology for X-ray, ultraviolet, infrared, and visible optics for space telescopes. Innovative precision optical substrates are needed with areal mass density of 20 kilograms per square meter with a 6 nanometers (nm) root mean square (RMS) surface contour. The challenge is improved material and manufacturing processes for optical quality on lower mass components. Lightweight optics enable reduction in optical structure requirements that translate to lower structure mass and improve stability. Large ultra-light precision optical structures technology advancement provides materials and methods to produce large aperture precision optical system structures. This technology is a way to mount the optics in a stable platform at the lowest mass. James Webb Space Telescope (JWST) represents the state of the art for monolithic optics and structures with dimensional stability down to 20 Kelvin (K). Materials and processes are needed to reduce optical system mass for the same performance. Achieving this by 2020 will enable large mirrors for future telescopes that will further improve science return and fundamental physics understandings.

Benefits of Technology

Future missions will benefit from optical system mass reduction, and improved optical performance. This will enable better science return through larger optical systems with precision exceeding current capability. Improved solar array cells will provide spacecraft with a lower mass for equivalent power generation. Electronics for extreme environments will allow mission extension through harsh environments for longer and more reliable and safer mission execution.

Table 25. TA 12.4.3 Technology Candidates – not in priority order

TA	Technology Name	Description
12.4.3.1	Photovoltaic Solar Cell Manufacturing	High efficiency solar cells production.
12.4.3.2	Optics Fabrication	Precision optic component materials and methods.
12.4.3.3	Special Electrical Process	Electrical components production for extreme environments electronics.
12.4.3.4	Large Ultra-Light Precision Optical Structures	Optical structures, materials, and methods to build precision large space-based science instrument structures.

TA 12.4.4 Sustainable Manufacturing

This area is focusing on environmentally sustainable practices that lead to improved performance, reduced waste, and a significantly reduced environmental footprint.

Technical Capability Objectives and Challenges

Sustainable manufacturing is defined as R&D for the design and manufacturing of products that minimize negative environmental and economic impacts. It aims to identify the sustainability areas that will have the greatest effect on mission architecture selection, and identify areas that pose the biggest threats and provide opportunities.

Technologies for today's aerospace design and manufacturing goals focus on mission objectives related to operability, reliability, and performance. Achieving these performance goals is often accomplished at the expense of life-cycle cost. Emerging technologies offer a strategic opportunity to improve affordability and accelerate execution time while performance standards are met. Reducing manufacturing operations such as assemblies and tooling; part count; and touch labor can dramatically reduce the cost of structures as can methods such as direct production of powder metallurgy of components for components like combustion devices.

Environmental technologies for aerospace materials and manufacturing processes availability are impacted by environmental and safety regulations, pollution prevention goals, and related supplier decisions. The aerospace community faces challenges with the availability of material supply chains during the life cycle of a program due to material obsolescence from new regulatory restrictions on production and use of traditional materials. Green production processes for major new manufacturing enterprises and production processes require a focus on environmental impact and sustainability. Today, implementation of green technology processes is slowed by lack of fundamental data, fragmentation of effort, and insufficient R&D programs. R&D for new chemical processes, new polymer and composite materials, paints, and coatings, and replacement processes for conventional metal finishing can transform manufacturing. Environmental issues are technically complex and materials changes involve significant program risk. Technologies are needed that reduce or eliminate the use of hazardous materials in production processes. Technologies are needed to replace hazardous materials such as hexavalent chromium and volatile organic compounds from manufacturing activities such as painting, coating, and cleaning.

Advanced energy systems provide innovation in materials and process technologies that are critical to achieving the longer-term objectives of an energy-efficient and low-carbon world. Renewable energy sources for future terrestrial and space development and energy-related materials and manufacturing for batteries and fuel cells, nuclear energy, and photovoltaics require development. Use of lifecycle analysis for manufacturing processes will enable agencies and organizations to identify where its environmental impact is the largest allowing for targeted reduction in waste, toxicity, and energy.

Benefits of Technology

Lower manufacturing productions costs can contribute significantly to economic sustainability. Sustainability is critical to NASA and the competitiveness of the Nation.

Table 26. TA 12.4.4 Technology Candidates – not in priority order

TA	Technology Name	Description
12.4.4.1	Environmental Technologies	Technologies that reduce or eliminate the use of hazardous materials in production processes; remove hazardous materials like hexavalent chromium and volatile organic compounds from manufacturing activities such as painting, coating, and cleaning; and green alternative energetic compounds.

TA 12.4.5 Nondestructive Evaluation and Sensors

NASA is manufacturing complex high-performance structures for space applications. These structural components must meet strict damage tolerance requirements. To ensure the quality of the structures, an accurate assessment of the as-built state is necessary. While tremendous improvements in manufacturing methods have resulted in the fabrication of more reliable components, manufacturing flaws do exist that can affect the performance of these materials. However, there are still fundamental limitations in the way NDE responses are correlated to the performance in materials.

Technical Capability Objectives and Challenges

A critical challenge for future vehicles is the development of systems that can ensure safety and reliability during ever increasing mission durations. Additionally, assessing and maintaining vehicle integrity with minimal human intervention is critically important. Accurate characterization of structural integrity requires in-situ sensor arrays to rapidly interrogate large areas and detect anomalies. Deployable NDE devices are used to perform accurate local assessments of these anomalies. Such sensor systems must be capable of detecting precursors of global degradation, as well as rapidly identifying and locating suddenly occurring mission threatening damage. This enables early mitigation against critical conditions to maintain integrity. Game-changing technology will be required to produce new sensors and NDE methodologies that are tailored to specific applications. A combination of fixed global sensor arrays along with autonomous inspection devices will be required for early detection, localization, and mitigation of critical conditions.

Benefits of Technology

The benefits of this technology include accurate and early detection of structural anomalies, rapid identification and location of potentially mission-threatening damage, and mitigation of critical conditions to maintain structural integrity. These benefits help to ensure mission safety and increase the reliability and maintainability of critical systems.

Table 27. TA 12.4.5 Technology Candidates – not in priority order

TA	Technology Name	Description
12.4.5.1	Nondestructive Evaluation (NDE) Sensor and Method	Computational NDE method and process for propulsion and in-space structures.

Appendix

Acronyms

3D	Three-Dimensional
ACP	Advanced Composites Project
ADC	Analog-to-Digital Converter
ALHAT	Autonomous Landing and Hazard Avoidance Technology
ARMD	Aeronautics Research Mission Directorate
BOL	Beginning-Of-Life
CMC	Ceramic Matrix Composites
DAC	Design Analysis Cycle
DDT&E	Design, Development, Test, and Evaluation
DRA	Design Reference Architecture
DRM	Design Reference Mission
EDL	Entry, Descent, and Landing
EVA	ExtraVehicular Activity
GEO-CAPE	GEOstationary Coastal and Air Pollution Events
ISAFR	In-Space Assembly, Fabrication, and Repair
ISS	International Space Station
JWST	James Webb Space Telescope
LEO	Low-Earth Orbit
MMOD	MicroMeteroid and Orbital Debris
NDE	NonDestructive Evaluation
NEA	Near-Earth Asteroid
NESC	NASA Engineering and Safety Center
OCT	Office of the Chief Technologist
PMC	Polymer Matrix Composites
PVDF	PolyVinyliDene Fluoride
PZT	PieZoelecTric
R&D	Research and Development
RF	Radio Frequency
SBKF	Shell Buckling Knockdown Factor
SHM	Structural Health Monitoring
SHM/THM	Structural Health Monitoring/Thermal Health Monitoring
SLS	Space Launch System
SOA	State Of the Art
TA	Technology Area
THM	Thermal Health Monitoring
TID	Total Ionizing Dose
TPS	Thermal Protection System
TRL	Technology Readiness Level
TTF	Time To Failure
USA	United States of America
U.S.	United States

Abbreviations and Units

Abbreviation	Definition
%	Percent
Å	Angstrom
Al	Aluminum
Al-Li	Aluminum Lithium
AM0	Air Mass 0 is the condition in space where there is NO air
$\alpha s/\varepsilon T$	Solar absorbance/thermal emittance
AU	Astronomical unit
C	Carbon
° C	Degree centigrade
cm	Centimeter
C/C	Carbon-Carbon
CVI	Chemical Vapor Infiltration
g	Grams
Gen	Generation
J	Joule
Kg	Kilograms
km	Kilometers
krad	1,000 units of absorbed radiation dose = 10 J/kg
kW	Kilowatt
M	Million
m	Meter
min	Minute
msec	Millisecond
N	Atoms/Nodes
nm	Nanometers
R-value	Measure of thermal resistance; under uniform conditions it is the ratio of the temperature difference across an insulator and the heat flux (heat transfer per unit area per unit time)
RMS	Root-mean-square
SiC	Silicon Carbide
t	Microseconds/Years/Decades
µm	Micrometer
UV	Ultraviolet
w	Watt
Whr	Watt-hour

Contributors

TECHNOLOGY AREA ROADMAP DEVELOPMENT TEAM

John Vickers
TA 12 Chair
NASA, Marshall Space Flight Center

LaNetra Tate
TA 12 Co-Chair
NASA, Headquarters

Faith Chandler
Director, Strategic Integration, OCT
NASA, Headquarters

Chris Coppens
NASA, Marshall Space Flight Center

Michael Dube
NASA, Langley Research Center

Sylvia Johnson
NASA, Ames Research Center

Pete Lillehei
NASA, Langley Research Center

David Lowry
NASA, Johnson Space Center

Kenny Segal
NASA, Goddard Space Flight Center

OTHER CONTRIBUTORS

Sharon Jeffries
NASA, Headquarters

Jennifer McMillian
NASA, Marshall Space Flight Center

Frank Ledbetter
NASA, Marshall Space Flight Center

Eric Poole
NASA, Headquarters

Mark Redlinger
Equator

Steve Scotti
NASA, Langley Research Center

Technology Candidate Snapshots

12.1 Materials
12.1.1 Lightweight Structures

12.1.1.1 Out Of Autoclave Material Systems Resins/Adhesives/Fibers

TECHNOLOGY

Technology Description: Resins, adhesives, and fibers whose properties result in large monolithic composite structures that have required performance for space applications.

Technology Challenge: Develop advanced polymeric matrix resins with high mechanical and functional properties and long out-life.

Technology State of the Art: Commercially available out of autoclave fibers and material systems. Adhesives systems lack maturity.

Parameter, Value:
Limited capabilities for material systems compared to autoclave processing (for example, mechanical, physical, thermal, etc.)

TRL: 4

Technology Performance Goal: Large composite structure without joints that has the required mechanical performance for space applications.

Parameter, Value:
Approach the capabilities of autoclave material systems (for example, mechanical, physical, thermal, etc.)

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Foundational research on resin and adhesive development, and processing methods for advanced polymer composites.

CAPABILITY

Needed Capability: Materials for large composite structures.

Capability Description: Provide materials for large monolithic composite structures for space applications.

Capability State of the Art: Large structures currently made by joining autoclaved parts.

Parameter, Value:
Autoclave size-limited capabilities for material systems (for example, mechanical, physical, thermal, etc.)

Capability Performance Goal: Large composite structure without joints that has the required mechanical performance for space applications.

Parameter, Value:
Approach the capabilities of autoclave material systems (for example, mechanical, physical, thermal, etc.)

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

12.1 Materials
12.1.1 Lightweight Structures

12.1.1.2 Low Mass, Multifunctional Materials

TECHNOLOGY

Technology Description: Materials that perform multiple functions in one structure through control of microstructure, composition, and architecture. See also 9.1 for description and requirements of multifunctional materials for entry, descent, and landing (EDL) systems.

Technology Challenge: Almost infinite number of materials systems and combinations. Relationships among microstructure, processing, and properties are complex. Must study to identify multifunctional materials that are most likely to yield the greatest improvements.

Technology State of the Art: Advances are being made but many more mechanical and functional properties can be combined. Improved understanding of microstructure, processing, and property relationships.

Parameter, Value:	TRL
Reduction of system mass that still provides all the necessary functions: 0%	2

Technology Performance Goal: Reduce system mass while retaining or improving the performance compared to current solutions that use different materials for different functions.

Parameter, Value:	TRL
Reduction of system mass that still provides all the necessary functions: 20%	5

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Foundational research covering the synthesis of multifunctional materials. For optimized multifunctional materials guidance from computationally designed materials TA 12.1.2 will be enabling. New manufacturing and characterization tools will facilitate the development of multifunctional materials.

CAPABILITY

Needed Capability: Achieve functional performance through material design.

Capability Description: Provide materials with properties that can be tailored to meet specific mission needs with lower system mass. Can include micrometeroid and orbital debris (MMOD) protection, radiation shielding, thermal protection, structural, self-sensing, power generation, energy harvesting, acoustic metamaterials, etc.

Capability State of the Art: Generally achieve performance by design of structures rather than through adjusting material properties.

Parameter, Value:

Reduction of system mass that still provides all the necessary functions: 0%

Capability Performance Goal: Reduce system mass while retaining or improving the performance compared to current solutions that use different materials for different functions.

Parameter, Value:

Reduction of system mass that still provides all the necessary functions: 20%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal	Enhancing	2033	--	2027	5 years

12.1 Materials
12.1.1 Lightweight Structures

12.1.1.3 Smart Materials

TECHNOLOGY

Technology Description: Materials that incorporate sensing functions with required mechanical and physical properties. See also 9.1 for description and requirements of multifunctional materials for EDL systems.

Technology Challenge: Incorporate accurate sensing functions while maintaining materials performance and system mass.

Technology State of the Art: Smart wing being developed for small unmanned aerial vehicles.

Parameter, Value:
Usefulness of the data;
Change in system mass;
Change in system or vehicle performance

TRL: 1

Technology Performance Goal: Need accurate and timely data describing the state of the system or vehicle.

Parameter, Value:
Usefulness of the data;
Change in system mass;
Change in system or vehicle performance

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Advanced manufacturing techniques (TA 12.4) and advanced sensing materials. Foundational research to develop or provide materials with advanced transduction capabilities that are compatible with other structural and functional materials.

CAPABILITY

Needed Capability: Materials for integrated system or vehicle health monitoring.

Capability Description: Provide distributed and continuous monitoring of the state of the material (heath, environment- temperature, pressure, etc.) without the use of external or embedded sensors.

Capability State of the Art: Sensing is not provided by a smart material. It is provided by the external or embedded sensors.

Parameter, Value:
Usefulness of the data;
Change in system mass;
Change in system or vehicle performance

Capability Performance Goal: Need accurate and timely data describing the state of the system and vehicle.

Parameter, Value:
Usefulness of the data;
Change in system mass;
Change in system or vehicle performance

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

12.1 Materials
12.1.1 Lightweight Structure

12.1.1.4 Self-Healing/Repair Materials

TECHNOLOGY

Technology Description: Materials that incorporate mechanisms that replace or that can be used for fast in-situ repair of damaged material.

Technology Challenge: Develop techniques to provide the self-healing or repair functions that do not degrade the mechanical properties or add significant mass. Focus is on small areas of damage on surfaces.

Technology State of the Art: Self-repairing systems include microencapsulation, vascular networks of reactive resins, puncture healing matrices. Repair materials include various patches and sealants.

Parameter, Value:

Parameter, Value	TRL
Micrometeroid and orbital debris (MMOD) velocity tests need to be conducted.	3

Technology Performance Goal: Lightweight, easy to use, repair technologies.

Parameter, Value:

Parameter, Value	TRL
Repair lifetime that will meet mission requirements.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Realistic understanding of the healing mechanisms that impart energy, enable material transport, and/or chemical reaction.

CAPABILITY

Needed Capability: Materials for repair.

Capability Description: Provide materials for repair or that can heal after damage and thus maintain the integrity of the vehicle or habitat to provide a safe environment.

Capability State of the Art: Current capability: if a material is damaged a patch is applied.

Parameter, Value:

Time required to identify damage and repair;

Size and magnitude of damage that can be repaired.

Capability Performance Goal: Robustness to MMOD damage.

Parameter, Value:

120 hours useful operation of the system after an MMOD strike.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

12.1 Materials
12.1.2 Computational Design

12.1.2.1 Predictive Computational Materials

TECHNOLOGY

Technology Description: Multiscale (nano-, meso-, micro-) modeling linking atomistic to continuum scales. Optimized materials with degradation understood and predicted throughout their service lives.

Technology Challenge: Developing efficient algorithms, bridging the time and length scales, simulation of complex physical processes in three-dimensions, developing the understanding of how to model the behavior of complex material systems, uncertainty quantification, verification and validation, computing power required, and the number and complexity of the materials systems.

Technology State of the Art: Larger systems ($N < 10^8$) and longer simulations time ($t < 1$ microsec.). Simulation volumes and times are limited by the number of atoms, elements, or nodes that can be stored and processed with the current computing capacity. This can lead to physically unrealistic predictions.

Parameter, Value:	TRL
Number of atoms and nodes capable of being modeled in a simulation ($N \sim 10^5$, $t \sim$ nanoseconds).	2

Technology Performance Goal: Computational models than can predict failure in a wide variety of materials and environments. Atomistic simulations that predict both qualitatively and quantitatively correct mechanisms. Mesoscale simulations that predict both qualitatively and quatitatively correct values. Robust predictive simulations with parameters calibrated using meso-scale and nano-scale simulations.

Parameter, Value:	TRL
Number of atoms and nodes capable of being modeled in a simulation ($N \sim 10^{10}$, $t \sim$ years/decades).	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Foundational research on the development of efficient algorithms. TA 11.1.2 Ground Computing, TA 11.3.5 Exascale Simulation, TA 11.3.6 Uncertainty Quantification, TA 11.3.7 Multiscale, Multiphysics and Multifidelity Simulation, and TA 11.3.8 Verification and Validation.

CAPABILITY

Needed Capability: Predict the performance of structural and multifunctional materials at operative length scales. This capability will enable design of aerospace materials as an analogous capability to computer-aided-design (CAD) of aerospace structures. Need the capability to predict functional performance and lifetime.

Capability Description: Provide a means of predicting materials behavior based upon first principals, backed up by experiment rather than generated completely by experimental data. Simulations are needed that can be used to predict the performance of the materials in their environments throughout the lifecycle from manufacture to retirement.

Capability State of the Art: Prediction of failure only possible for simple microstructures possible.

Parameter, Value:

Number of atoms and nodes capable of being modeled in a simulation ($N \sim 10^5$, $t \sim$ nanoseconds)

Capability Performance Goal: Accurate property and chemical structure relationships linked to external environments. Complex three-dimensional (3D) microstructures with atomistically derived constitutive relations. Robust, predictive methodologies that can be used to design materials at their operative length scales.

Parameter, Value:

Larger systems ($N > 10^8$) and longer simulations time ($t > 1$ microsec.)

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-Boom, Low-Noise, and Low-Emmission Supersonic Transports	Enhancing	--	--	2035	10 years

12.1 Materials
12.1.2 Computational Design

12.1.2.2 Computational Materials Design

TECHNOLOGY

Technology Description: Multiscale (nano-, meso-, micro-) modeling linking atomistic to continuum scales. Computational design models for design of structural, thermal, and functional materials.

Technology Challenge: Link computational materials design with current and emerging materials synthesis and processing techniques. Computing power required, developing the algorithms, developing the understanding of how to model the behavior of complex systems, and the number and complexity of the materials systems.

Technology State of the Art: Thermodynamic-based software packages based on calculation of phase diagrams used to predict microstructures in simple processes such as castings. Primarily equilibrium phases only.

Parameter, Value:

Number of atoms and nodes capable of being modeled in a simulation ($N \sim 10^5$, $t \sim$ nanoseconds).

TRL 2

Technology Performance Goal: Computational models than can predict material's properties and design compositions, microstructures, and architectures with desired functional properties.

Parameter, Value:

Number of atoms and nodes capable of being modeled in a simulation ($N \sim 10^{10}$, $t \sim$ years/decades).

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Foundational research in emerging materials synthesis and processing techniques. TA 11.1.2 Ground Computing, TA 11.3.5 Exascale Simulation, TA 11.3.6 Uncertainty Quantification, TA 11.3.7 Multiscale, Multiphysics and Multifidelity Simulation, and TA 11.3.8 Verification and Validation.

CAPABILITY

Needed Capability: Design more capable materials through computational methods. This capability will enable design of aerospace materials as an analogous capability to computer-aided-design (CAD) of aerospace structures.

Capability Description: Provide a means of modifying a material's properties based upon first principals. Simulations that can be used to design materials that are optimized for their intended usage, including loadings and environments, throughout the vehicle's lifecycle from manufacture to retirement.

Capability State of the Art: Prediction of capabilities for design in early stage. Materials design is conventionally done by trial-and-error and results in sub-optimized materials.

Parameter, Value:

Number of atoms and nodes capable of being modeled in a simulation.

Capability Performance Goal: Accurate property/chemistry/microstructure relationships. Complex three-dimensional (3D) microstructures with atomistically derived constitutive relations.

Parameter, Value:

Larger systems ($N > 10^8$) and longer simulations ($t > 1$ microsec.).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-Boom, Low-Noise, and Low-Emmission Supersonic Transports	Enhancing	--	--	2035	10 years

12.1 Materials
12.1.2 Computational Design

12.1.2.3 Experimental Verification Technique

TECHNOLOGY

Technology Description: Characterization techniques for materials at length scales that allow for verification of nano-, meso-, and micro-scale models.

Technology Challenge: Development of techniques for quantitiative microscopy at length scales from nanometers to microns; development of methods for reconstruction of volumes of material in three-dimensions; determination of the relationships between input parameters, microstructure, and material response; and quantification of physical processes involving multiple inter-related phenomena.

Technology State of the Art: Imprecise determination of physical processes and their relationships across length scales.

Parameter, Value:	TRL
Accurate determination of structure and composition at the appropriate length scales.	3

Technology Performance Goal: Quantitative determination of physical processes and their relationships across length scales.

Parameter, Value:	TRL
Accurate determination of structure and composition at the appropriate length scales.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: The development of new in-situ high-resolution microscopy and spectroscopy techniques; TA 11.4.1 Science, Engineering, and Mission Data Lifecycle, TA 11.4.2 Intelligent Data Understanding, and TA 11.4.3 Semantic Technologies.

CAPABILITY

Needed Capability: Design of structural and multifunctional materials at operative length scales. This capability will enable design of aerospace materials as an analogous capability to computer-aided-design (CAD) of aerospace structures.

Capability Description: Verification of models and experiments to enable design of materials at all length scales.

Capability State of the Art: Many techniques available or under development. Techniques not widely available and linkage between length scales is challenging.

Parameter, Value:

Time to develop and incorporate new aerospace materials: 15 to 20 years.

Capability Performance Goal: Characterization and verification techniques that cover length scales and result in reliable methods for materials design.

Parameter, Value:

Time to develop and incorporate new aerospace materials: 1 to 5 years.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Innovation in Commercial Supersonic Aircraft: Introduction of Affordable, Low-Boom, Low-Noise, and Low-Emmission Supersonic Transports	Enhancing	--	--	2035	10 years

12.1 Materials
12.1.3 Flexible Material Systems

12.1.3.1 Structural Textile Material

TECHNOLOGY

Technology Description: Structural textile material that provides shape and integrity to inflatable habitats and deployable structures. See also 9.1.1.

Technology Challenge: Increase ultimate tensile strength while reducing mass and increasing lifetime of the textile reinforcements.

Technology State of the Art: Large structure capability, for example, ground-based demo for space application.

Parameter, Value:	TRL
Kevlar straps for the inflatable module have been evaluated to multi millennia time to failure (TTF) at 10% ultimate tensile strain	5

Technology Performance Goal: Mass efficient materials solutions for long lifetime, high volume habitats.

Parameter, Value:	TRL
TTF greater than mission durations (plus a factor of safety) at greater than 30% ultimate tensile strain	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Expandable habitats.

Capability Description: Lightweight deployed human habitats for space or Mars surface, and large space, lunar, or planetary-based observation platforms. Develop a 7 to 9 meter inflatable habitat capable of a 540-day Mars surface mission.

Capability State of the Art: Inflatable module on the International Space Station (ISS) in 2015. Inflatable module with Kevlar woven reinforcement straps.

Parameter, Value:

Structural lifetime.

Capability Performance Goal: For ISS: sufficient lifetime for the life of the station or mission. Habitats for deep space transportation: sufficient lifetime for the duration of transit plus sufficient factor of safety. For planetary habitats: multi-decade lifetime.

Parameter, Value:

Structural lifetime:

ISS: 5 years plus factor of safety;

Habitats for deep space transportation: 2 to 3 years plus a factor of safety;

Planetary habitats: 20 years plus a factor of safety

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years

12.1 Materials
12.1.3 Flexible Material Systems

12.1.3.2 Ultra-Lightweight Flexible Material

TECHNOLOGY

Technology Description: Ultra-lightweight substrate that is an efficient photon energy transducer. More mass efficient than metalized films with sufficient thermal and mechanical durability and flexibility for packaging, deployment, and a long-duration mission. Refer to 2.2.2 for further descriptions of materials suitable for solar sails.

Technology Challenge: Low areal density, space-durable membrane substrate material; high reflectivity and high emissivity, conductive membrane substrate coating; and large-area, ultra-thin (< 1 micron) membrane manufacturing, coating, and handling processes. Reliable packaging and deployment in space.

Technology State of the Art: International solar sail used an aluminum deposited polyimide membrane. 20 m x 20 m ground system level demonstration or conceptual ideas for solar sails.

Parameter, Value:

Areal density;

Opacity;

Durability/lifetime in space environment;

Efficiency of the momentum transfer;

Thermal stability/control

TRL: 3

Technology Performance Goal: Ultra-low areal density solar sail membrane system with sufficient thermal stability, mechanical durability, and space radiation tolerance for space mission operations ranging 0.25 AU outwards.

Parameter, Value:

Areal density;

Opacity;

Durability/lifetime in space environment;

Efficiency of the momentum transfer;

Thermal stability/control;

Coordinated with TA 2.2 solar sail propulsion:

1st Gen) 3 µm thickness: 1,600 m^2

2nd Gen) 2-3 µm thickness: 22,500 m^2

3rd Gen) < 2 µm thickness: 90,000 m^2

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Ultra-large area, low areal density, space durable, membrane materials for solar sail structures.

Capability Description: Provide materials for efficient transfer of photon momentum to enable solar sail propulsion.

Capability State of the Art: International space agency demonstrated a 20 m solar sail as a propulsion system for a Venus flyby mission.

(1989, concept) KaptonTM (7.62 µm), aluminum (0.1 µm), 1,200 m^2;

(International agency sail, 2010, launched) Polyimide (7.5-8.5 µm), aluminum (~0.08 µm), 196 m^2;

(NASA 2011, concept) Mylar (2.54 µm) deposited aluminum (0.1 µm) and chrome (1,000 Å), 960 m^2

Parameter, Value:

Areal density;

Opacity;

Durability/lifetime in space environment;

Efficiency of the momentum transfer;

Thermal stability/control

Capability Performance Goal: Coordinated with TA 2.2 solar sail propulsion:

1st Gen (~1 AU, > 10 years): ultra-lightweight durable solar sail membranes for spacecraft station keeping at Lagrange Point sub-L1 along the Sun/Earth Line;

2nd Gen (~0.25 AU to 2 AU, > 10 years): ultra-lightweight durable solar sail membranes for spacecraft in a heliocentric orbit with semi-major axis of 0.48 AU;

3rd Gen (~0.25 AU to reach 250 AU within 20 years of launch): ultra-lightweight durable solar sail membranes for spacecraft to enable a Voyager class spacecraft

Parameter, Value:

1st Gen (~1 AU, > 10 years): ~ 5 g/m^2 areal density of reflectance membrane, UV (~0.75 J/cm^3•min) and ionizing radiation (10-100 R/hr) tolerance;

2nd Gen (~0.25 AU to 2 AU, > 10 years): 3 to 5 g/m^2 areal density of reflectance membrane, UV (~0.75 J/cm^3•min) and ionizing radiation (10-100 R/hr) tolerance, low $\alpha s/\varepsilon T$ (solar absorbance/thermal emittance, < 0.2), low thermal stress;

3rd Gen (~0.25 AU to reach 250 AU within 20 years of launch) < 3 g/m^2 areal density of reflectance membrane, UV (~0.75 J/cm^3•min) and ionizing radiation (10-100 R/hr) tolerance, low $\alpha s/\varepsilon T$ (solar absorbance/thermal emittance, <0.1), low thermal stress

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Solar Wind Measurements	Enabling	--	On-going	--	10 years

12.1 Materials
12.1.3 Flexible Material Systems

12.1.3.3 Smart Flexible Material

TECHNOLOGY

Technology Description: Fabrication or processing of material that will change shape according to need. This material may incorporate multiple functions like sensing and solar or space radiation shielding with required mechanical and physical properties. The material includes shape memory alloys, shape memory polymers, bimetal, piezoelectric materials (piezeoelectric (PZT) laminates or polyvinylidene fluoride (PVDF)), phase change materials, photo-active-actuators, and/or magnetostrictive material.

Technology Challenge: Material that incorporates sensing and actuating functions with required mechanical, physical properties. Cycling stability, reduction, or elimination of power requirements.

Technology State of the Art: Morphing structures for wings under development. Preliminary identification and process refinement of shape memory materials and self actuating and morphing materials.

Parameter, Value:	TRL
Cycling speed; Power requirements; Size; Mass; Shape control/accuracy; Throw	2

Technology Performance Goal: Material able to reconfigure in response to external load or stimulus and lock into desired configuration. Desire is to reconfigure without the need for external actuators or sensors.

Parameter, Value:	TRL
Cycling speed (response time < msec, reliable cycle > 10^8 runs); Power efficiency: > 90%; Size; Mass: 20% reduction for structure; Shape control/accuracy: shape fixed rate > 99.9%, shape recovery rate > 99.9%; Throw	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Foundational materials research to expand the Curie temperatures of these material classes, the development of cryogenically stable material packing concepts.

CAPABILITY

Needed Capability: Shape-morphing materials.

Capability Description: Provide shape-morphing material for a variety of applications. i.e., control surfaces, deployable reentry vehicles, expandable habitats, and deformable mirrors. Material able to reconfigure in response to external load or stimulus and lock into desired configuration.

Capability State of the Art: Morphing structures are currently not in use in structural aerospace applications.

Parameter, Value:
Cycling speed;
Power requirements;
Size;
Mass;
Shape control/accuracy;
Throw;
Radiation shielding;
MMOD protection

Capability Performance Goal: Material able to reconfigure in response to external load or stimulus and lock into desired configuration. Desire is to reconfigure without the need for external actuators or sensors. Multifunctionality such as solar and space radiation shielding, MMOD impact protection, and self-health monitoring are desired.

Parameter, Value:
Cycling speed (response time < msec, reliable cycle > 10^8 runs);
Power efficiency: > 90%;
Size;
Mass: 20% reduction for structure;
Shape control/accuracy: shape fixed rate > 99.9%, shape recovery rate > 99.9%;
Throw;
Radiation shielding: 20% level of polyethylene; MMOD protection: 1 to 70 km/s

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enabling	--	--	2025	10 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vertical Lift Vehicle Efficiency and Environmental Performance in 2035	Enabling	--	--	2035	10 years

12.1 Materials
12.1.4 Environment

12.1.4.1 Cryo-Insulator Material

TECHNOLOGY

Technology Description: More reliable and efficient materials for cryo-insulator, with increasing R-value, lower densities, and reduced thicknesses (see also TA 14).

Technology Challenge: Low-density and thin cryo-insulator for more efficient cryo-liquid storage tank.

Technology State of the Art: Current cryo-insulators have limited insulating capacity on a per weight and thickness basis.

Parameter, Value:	TRL
Thermal conductivity; Mass; Impact resistance; Strength	3

Technology Performance Goal: Low mass and extremely low thermal conductivity material with adequate mechanical properties.

Parameter, Value:	TRL
Thermal conductivity; Mass; Impact resistance; Strength	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: The development of advanced cryo-insulators with high thermal resistivity and low density.

CAPABILITY

Needed Capability: Maintain internal cryogenic temperatures and/or protect from external cryogenic temperatures.

Capability Description: Lightweight, large-scale fuel tanks for in-space depots with near zero boil off.

Capability State of the Art: Current insulation provides cryo storage times of less than 12 hours in the space environment.

Parameter, Value:

Thermal conductivity;

Mass;

Impact resistance;

Strength

Capability Performance Goal: Propellant mass boil-off rate: Passive loss rate less than 4% mass per month. Efficiently protect habitat and vehicle structures from cryogenic environment.

Parameter, Value:

Propellant mass boil-off rate: passive loss rate less than 4% mass per month;

Thermal conductivity;

Mass;

Impact resistance;

Strength

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years

12.1 Materials
12.1.4 Environment

12.1.4.2 High/Ultra-High Temperature Material

TECHNOLOGY

Technology Description: Advanced superalloy and ceramic matrix composite, ultra-high temperature ceramic, high temperature insulator, refractory composite, and thermal and environmental coating (see also 9.1.1 for high temperature, structural materials)..

Technology Challenge: Develop material that is oxidation resistant while maintaining strength and toughness at high temperatures. Opacified fibrous insulation with extreme temperature capable fibers (1,650° C) must be developed. Fabrication techniques for large-scale systems and relevant flight demonstration.

Technology State of the Art: Ceramic matrix composites under development for structural and propulsion applications. Environmental resistance still requires additional research. International space agency is flying chemical vapor infiltration carbon (C)/silicon carbide (SiC). Ultra-high temperature ceramics with improved properties are under development and testing.

Parameter, Value:

Temperature: values depend on specific applications;

Erosion and corrosion resistance: values depend on specific applications;

Structural performance: values depend on specific applications;

Lifetime in relevant environment: values depend on specific applications;

System mass: values depend on specific applications.

TRL

2

Technology Performance Goal: Engines and structures that can operate higher temperatures and maintain structural performance at higher temperatures with reduced mass.

Parameter, Value:

Temperature: values depend on specific applications;

Erosion and corrosion resistance: values depend on specific applications;

Structural performance: values depend on specific applications;

Lifetime in relevant environment: values depend on specific applications;

System mass: values depend on specific applications.

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Foundational research on materials more resistant to oxidizing environments, which have the required mechanical properties, and are able to be manufactured into the required structures.

CAPABILITY

Needed Capability: Structural and functional performance at high temperatures.

Capability Description: Provide material that enables high performance structures capable of operating at ultra-high temperatures and/or reactive environments. This includes propulsion applications (sustained use at temperatures between 1,200 to 1,500° C in high erosion and reactive environments), thermal and structural applications from 1,300° C to in excess of 1,650° C (composite airframe control surfaces, leading edges, and insulation).

Capability State of the Art: Current materials erode and degrade under the environmental exposure of rocket engines, which limits launch lifting capability. Advanced superalloys in use in jet engines. Advanced carbon carbon (C-C) and C-SiC capable to ~1,650° C. Ultra-high temperature ceramics have higher temperature capability.

Parameter, Value:

Temperature: values depend on specific applications;

Erosion/corrosion resistance: values depend on specific applications;

Structural performance: values depend on specific applications;

Lifetime in relevant environment: values depend on specific applications;

System mass: values depend on specific applications.

Capability Performance Goal: Engines and structures that can operate higher temperatures and maintains structural performance at higher temperatures with reduced mass.

Parameter, Value:

Temperature: values depend on specific applications;

Erosion/corrosion resistance: values depend on specific applications;

Structural performance: values depend on specific applications;

Lifetime in relevant environment: values depend on specific applications;

System mass: values depend on specific applications.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	10 years

12.1 Materials
12.1.4 Environment

12.1.4.3 Coatings

TECHNOLOGY

Technology Description: Thermal, environmental, tribological, optical, and special coatings.

Technology Challenge: Durability, specific performance, and compatability with the substrate.

Technology State of the Art: Coatings are available for many applications.

Parameter, Value:

Lifetime in relevant environment: values depend on specific applications;

Performance of a specific function in a relevant environment: values depend on specific applications.

TRL: 3

Technology Performance Goal: Need coating that is more durable, more easily applied, more efficient, and has a higher performance.

Parameter, Value:

Lifetime in relevant environment: values depend on specific applications;

Performance of a specific function in a relevant environment: values depend on specific applications.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Foundational research on the development of coatings for high temperature composites.

CAPABILITY

Needed Capability: Protection from external environments and specific functions for surfaces.

Capability Description: Provide protection or capability and thus improve lifetime and performance of materials.

Capability State of the Art: Materials used for structural or functional applications are subject to degradation due to the external environment. Materials may lack the specific surface properties needed to perform functions efficiently.

Parameter, Value:

Lifetime in relevant environment: values depend on specific applications;

Performance of a specific function in a relevant environment: values depend on specific applications

Capability Performance Goal: Materials and structures that can operate for longer lifetimes, in more severe environments, and can operate more efficiently and safely.

Parameter, Value:

Lifetime in relevant environment: values depend on specific applications;

Performance of a specific function in a relevant environment: values depend on specific applications

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	10 years

12.1 Materials
12.1.4 Environment

12.1.4.4 Extreme Temperature / Radiation Hardened Electronic Material

TECHNOLOGY

Technology Description: Extreme temperature, radiation hardened integrated circuit material (see also TA 11.1.1).

Technology Challenge: Electronic material needs to be developed that can operate over wider temperature ranges and that can operate in high radiation environments.

Technology State of the Art: Current strategies are to protect the electronics in thermally controlled enclosures and provide significant radiation shielding layers. Silicon-germanium (SiGe) based analog electronics have been developed that can operate reliably to 100 krad at temperatures in the range of 150° to +180° C. Digital electronics have been shown to operate at > 100 krad and temperatures in the range of -180° to +180° C.

Parameter, Value:

Temperature capability and radiation resistance;

Radiation total ionizing dose (TID): 100 krad;

Operating temperature: -200° to +200° C

TRL 2

Technology Performance Goal: Material capable of performance at much wider temperature ranges and in the space environment with minimal shielding suitable for mission duration.

Components must have 15-year life and stable operation at 100 krad, and -200° to +200° C temperature range. Components required include microprocessors, memories, interconnects, passives, amplifiers, analog-to-digital converters (ADCs), current sources, voltage references, and associated packaging.

Parameter, Value:

Temperature capability and radiation resistance;

Radiation TID: 100 krad;

Operating temperature: -200° to +200° C

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Foundational materials research concerning semiconductor materials. TA 12.4.3 Electronics and Optics Manufacturing Process.

CAPABILITY

Needed Capability: Radiation hardened electronic material (including semiconductors, solders, connectors, contacts, and capacitor materials) that can operate over a wide range of temperatures.

Capability Description: Provide materials for extreme temperature, radiation hardened integrated circuit electronics that operate well beyond the capability window of current electronic materials. Complete electronic assembly materials sets need to be evaluated and developed, including integrated circuits, interconnects, board materials, and passive devices.

Capability State of the Art: SiGe based analog electronics have been developed that can operate reliably to 100 krad at temperatures in the range of -150° to +180° C. Digital electronics have been shown to operate at > 100 krad and temperatures in the range of -180° to +180° C.

Parameter, Value:

Radiation TID: 100 krad;

Operating temperature: -150° to +180° C

Capability Performance Goal: Integrated circuit electronics that operate well beyond the capability window of current electronic materials. Components must have 15-year life and stable operation at 100 krad, and -200° to +200° C temperature range. Components required include microprocessors, memories, interconnects, passives, amplifiers, ADCs, current sources, voltage references, and associated packaging.

Parameter, Value:

Temperature capability and radiation resistance;

Radiation TID: 100 krad;

Operating temperature: -200° to +200° C

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enabling	--	2023*	2020	5 years
Discovery: Later Discovery Program	Enabling	--	2026	2023	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

12.1 Materials
12.1.4 Environment

12.1.4.5 Material for Combined Extreme Environments

TECHNOLOGY

Technology Description: Development of material that combines resistance to extreme radiation, thermal, chemical (corrosive), and pressure environments.

Technology Challenge: Material needed to withstand the extreme temperatures, pressures, and highly corrosive environments such as the Venus atmosphere or extreme environment locations on Earth or other planets.

Technology State of the Art: Traditional materials are limited to 1 to 2 hour data collection durations at Venus. Longer-duration materials need to be developed to extend data collection time.

Parameter, Value:

Temperature capability: values depend on application/mission;

Strength: values depend on application/mission;

Corrosion resistance: values depend on application/mission;

Lifetime: hours.

TRL

2

Technology Performance Goal: Material that can operate in the extreme environment for weeks and months.

Parameter, Value:

Temperature capability: values depend on application/mission;

Strength: values depend on application/mission;

Corrosion resistance: values depend on application/mission;

Lifetime: weeks to months.

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Material property database for materials that resist degradation in extreme environments.

CAPABILITY

Needed Capability: Material with demonstrated capability for long-term resistance to extreme combined environments.

Capability Description: High temperature, sulfuric acid resistant material and adhesive for use in Venus atmosphere.

Capability State of the Art: Traditional materials can withstand a few hours before loss of function. This limits data collection time to 1 to 2 hours.

Parameter, Value:

Temperature capability: values depend on application/mission;

Strength: values depend on application/mission;

Corrosion resistance: values depend on application/mission;

Lifetime: hours.

Capability Performance Goal: Demonstrate use in extreme environments, i.e., Venus atmosphere and Earth extreme environments (e.g., volcanoes, deep-sea vents).

Parameter, Value:

Temperature capability: values depend on application/mission;

Strength: values depend on application/mission;

Corrosion resistance: values depend on application/mission;

Lifetime: weeks to months.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

12.1 Materials
12.1.5 Special Materials

12.1.5.1 Durable Lightweight Optically Transparent Material

TECHNOLOGY

Technology Description: Optical material that can be deployed and durable material for observation platforms with high optical performance. All materials must be lightweight. There are concepts for polymeric and glass hybrid and transparent composite systems.

Technology Challenge: Make lightweight hybrid or composite system of the appropriate size and durability while maintaining the required optical performance.

Technology State of the Art: Current systems utilize heavy, triple redundant systems to ensure safety.

Parameter, Value:

Density: values depend on specific applications;

Durability: values depend on specific applications;

Deployment: values depend on specific applications;

Optical performance: values depend on specific applications.

TRL

2

Technology Performance Goal: Optical material for high-strength, lightweight, low-scatter windows for habitat and observation platforms and deployable, shape-changing solar concentrators for power and thermal energy.

Parameter, Value:

Density: values depend on specific applications;

Durability: values depend on specific applications;

Deployment: values depend on specific applications;

Optical performance: values depend on specific applications.

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Clear and colorless space durable polymer development. Polymer and glass hybrid composite processing.

CAPABILITY

Needed Capability: Windows for habitats and observation platforms.

Capability Description: Provide optical materials for high-strength, lightweight, low-scatter windows for habitat and observation platforms, and deployable, shape-changing solar concentrators for power and thermal energy.

Capability State of the Art: Current materials systems are heavy. Deployment capability is insufficient for concentrator applications. Lightweight windows for expandable habitats have not been demonstrated.

Parameter, Value:

Density: values depend on specific applications;

Durability: values depend on specific applications;

Deployment: values depend on specific applications;

Optical performance: values depend on specific applications.

Capability Performance Goal: Optical material for high-strength, lightweight, low-scatter windows for habitat and observation platforms, and deployable, shape-changing solar concentrators for power and thermal energy.

Parameter, Value:

Density: values depend on specific applications;

Durability: values depend on specific applications;

Deployment: values depend on specific applications;

Optical performance: values depend on specific applications.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

12.1 Materials
12.1.5 Special Materials

12.1.5.2 Lightweight Space Suit Material

TECHNOLOGY

Technology Description: Durable material that performs multiple functions to eliminate single function layers in current suit designs. Current layers include air bladder, restraint layer, insulation, and micrometeoroid protective layer. Self-healing functions are desirable (refer to TA 6.2.1 for further EVA spacesuit descriptions).

Technology Challenge: Develop durable multifunctional, self-healing fiber and fabric.

Technology State of the Art: Space suits composed of single function, multiple material layers.

Parameter, Value:

Areal mass;

Durability;

Flexibility;

Weight: 0.35 lbs per square foot of layup;

Lifetime: 25 extravehicular activities (EVAs) without servicing, maintenance, or change out;

Thermal: e* = 0.085;

No self-healing capability.

TRL: 2

Technology Performance Goal: Durable mass-efficient flexible space suit material with self-healing functions.

Parameter, Value:

Areal mass;

Durability;

Flexibility;

Mass: 25% reduction;

Lifetime: 100 EVAs or 800 hours of use; Thermal e* = 0.085 or better;

Self-healing within 5 seconds after a 1 inch long cut.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Foundational materials research for textile materials; TA 6.2.1: Pressure Garment, TA 6.4.3.2 Advanced Clothing, and TA 12.1.3.1 Structural Textiles.

CAPABILITY

Needed Capability: Durable, lightweight space suits.

Capability Description: Provide mass-efficient flexible space suit materials with self-healing functions.

Capability State of the Art: Current spacesuits consist of multiple single function layers (pressure garment, restraint layer, thermal insulation, thermal cooling, debris strike protection, and minimal cut/rip resistance) and thus impede the dexterity of the astronauts. Gloves provide additional cut resistant and durability than the rest of the suit layup. Currently no self-healing functions are included.

Parameter, Value:

Areal mass: values depend on specific applications;

Durability: values depend on specific applications;

Flexibility: values depend on specific applications.

Capability Performance Goal: Enhanced human mobility and endurance for EVA exposure.

Parameter, Value:

Areal mass: values depend on specific applications;

Durability: values depend on specific applications;

Flexibility: values depend on specific applications.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

12.1 Materials
12.1.5 Special Materials

12.1.5.3 Power Generation and Energy Storage Material

TECHNOLOGY

Technology Description: Material for fuel cells (solid oxide, polymer electrolyte membrane), batteries, capacitors, and energy harvesting devices (solar, thermal, vibration, kinetic energy).

Technology Challenge: New materials and architectures that can be incorporated into a lightweight efficient power generation and energy storage system.

Technology State of the Art: Fuel cells, photovoltaics, thermal electrics, batteries, and capacitors are all currently in use. There is a desire for higher performance systems from a power density and energy density perspective. Large-scale electric harvesting systems are operational for low-temperature applications.

Parameter, Value:
Energy density: 200 Whr/kg;
Power density: 50 to 100 W/kg

TRL
2

Technology Performance Goal: Materials that achieve higher energy generation and storage efficiency.

Parameter, Value:
Energy density: greater than 400 Whr/kg;
Power density: greater than 100 W/kg

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Foundational materials research on materials to enable new or enhanced power generation and energy storage applications; TA 3.1 Power Generation and TA 3.2 Energy Storage.

CAPABILITY

Needed Capability: Power generation and energy storage.

Capability Description: Provide material systems to efficiently generate power and store energy in space.

Capability State of the Art: Fuel cells, photovoltaics, thermal electrics, batteries, and capacitors are all currently in use. There is a desire for higher performance systems from a power density and energy density perspective. Large-scale electric harvesting systems are operational for low-temperature applications.

Parameter, Value:
Energy density: 200 Whr/kg;
Power density: 100 W/kg

Capability Performance Goal: Improve efficiency of power generation and storage.

Parameter, Value:
Energy density: greater than 400 Whr/kg;
Power density: greater than 100 W/kg

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

12.2 Structures
12.2.1 Lightweight Concepts

12.2.1.1 Out-of-Autoclave Primary Structure

TECHNOLOGY

Technology Description: Design and economic fabrication of large structure without autoclave pressure that is useful for both large components and for bonding of assemblies outside an autoclave.

Technology Challenge: Structural concepts and fabrication approaches that result in consistent quality and high structural efficiency for large out-of-autoclave structural assemblies. Reliable out-of-autoclave bonding of primary structures without degradation over multiple bonding thermal cycles during the assembly process.

Technology State of the Art: Limited capabilities for out-of-autoclave structures compared to autoclave performance.

Parameter, Value:	TRL
Mechanical performance (strength, durability): values depend on application.	4

Technology Performance Goal: Reliable structural component that approaches the performance of autoclaved structure. Reduce mass by eliminating bolted joints.

Parameter, Value:	TRL
Mechanical performance equivalent to autoclaved structure.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Development of families of non-autoclave adhesives that cover a range of cure temperatures and that are robust to processing conditions.

CAPABILITY

Needed Capability: Large unitized structure.

Capability Description: Provide large unitized composite structure for space applications.

Capability State of the Art: Large structures are currently made by joining autoclaved parts in the autoclave or by bolting. Autoclave size limits the size of unitized structures. Out-of-autoclave bonded joints are typically inferior to autoclave bonded joints.

Parameter, Value:
Unitized structure size and joint strength/durability.

Capability Performance Goal: Large, unitized composite structure that has the required mechanical performance for space applications.

Parameter, Value:
Unitized structure size and joint strength/durability.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.1 Lightweight Concepts

12.2.1.2 Composite Cryogenic Tank

TECHNOLOGY

Technology Description: Large composite cryogenic tank for launch vehicles and in-space propellant depots.

Technology Challenge: Increasing design strain from a leakage-limited value towards strength allowables to reduce mass. Localized stresses require improved design concepts and/or validated, higher-fidelity analysis to increase design margins. Cyclic and long-term storage tests are needed to verify that permeability is minimized.

Technology State of the Art: Intermediate sized (2 to 3 meter) composite cryogenic tanks have been produced and tested. A 5.5 meter tank has been fabricated and will be tested (to achieve Technology Readiness Level 5).

Parameter, Value: Limited tank size with leak-free performance.

TRL: 4

Technology Performance Goal: Mechanical and leak-free performance of tank at low mass up to 8.4 meter tank diameter.

Parameter, Value: 8.4 meter tank diameter meeting structural and leakage requirements; 30% tank weight savings over metallic tanks.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Development of critical joints (splice, Y-joints) and interfaces meeting structural and functional requirements.

CAPABILITY

Needed Capability: Lightweight propellant tank.

Capability Description: Primary tank structure of composites instead of metals for propellent depots and heavy lift exploration system (e.g., Space Lanch System, or SLS) and human exploration upper stages.

Capability State of the Art: State of the art for cyrogenic tanks is friction-stir-welded aluminum lithium 2195 stiffened structure.

Parameter, Value: Composite cryogenic demo tanks (up to 2.5 meter diameter) have been developed and tested.

Capability Performance Goal: Full-scale, SLS-stage-class tank with reduced mass over metallic tanks.

Parameter, Value: Validated, spacecraft composite cryogenic tank up to 8.4 meter diameter.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.1 Lightweight Concepts

12.2.1.3 Composite and Inflatable Habitat

TECHNOLOGY

Technology Description: Polymer matrix composites (PMCs) and inflatable habitat.

Technology Challenge: Improved understanding and predictability of mechanics and durability of soft goods (for example, creep) and composites (for example, atmosphere leakage) to characterize habitat performance. Composite damage tolerance and robustness including nondestructive evaluation of joints and bonds. Soft shell to rigid core Interface technology and process development.

Technology State of the Art: Composite Crew Module ground demo tested. Composites are in widespread use in aeronautic primary structures, but not in any space habitation applications.

Parameter, Value: TRL 3

Limited data on composites and softgoods for stringent space habitation applications.

Technology Performance Goal: Validation that composites and softgoods can meet space habitation structural and functional requirements.

Parameter, Value: TRL 6

Mechanical and functional performance (including expandable volume as required) at low mass.

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Human habitable modules for long-term, deep space missions.

Capability Description: Dramatic increases in working volume from launch volume and/or dramatic decreases in mass of the primary structure from SOA with improved radiation protection.

Capability State of the Art: International Space Station modules.

Parameter, Value:

Percent SOA mass reduction: 0 to 5%;

Develop inflatable volume expandability: 2:1 to 4:1

Capability Performance Goal: In-space habitats for multi-year missions with reduced mass and/or expandabilty.

Parameter, Value:

Percent SOA mass reduction: 50%;

Develop inflatable volume expandability: 10:1

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.1 Lightweight Concepts

12.2.1.4 Very Large Solar Array Structure

TECHNOLOGY

Technology Description: 100 to 1,000 kW class solar array structure.

Technology Challenge: Developing solar array structure for solar electric powered vehicles (and other in-space uses) for up to 1,000 kW class systems within constraints of finite launch vehicle fairing sizes and payload mass limits, and ensuring their reliable deployment and operation in space.

Technology State of the Art: Near-term solar eletric powered missions will use solar arrays in the 20 to 50 kW power class; presently NASA is addressing this need.

Parameter, Value: Meeting structural and functional requirements for 30 kW class systems.

TRL: 3

Technology Performance Goal: Up to 1,000 kW class system needs to be lightweight, stowed compactly for launch, be deployed autonomously, and have sufficient rigidity to avoid deleterious control-structures interactions.

Parameter, Value: Meeting structural and functional requirements for ~1,000 kW class systems.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Large capacity solar electrical power for in-space applications.

Capability Description: Large quantities of electricity are needed for in-space transportation (for example, solar electic powered), waypoints, and depots; solar power is the primary method for its generation.

Capability State of the Art: International Space Station solar power arrays approximately span a football field in area, generate 84 kW in power and were incrementally deployed by crew over many years.

Parameter, Value: Power: 84 kW

Capability Performance Goal: Up to 1,000 kW lightweight solar array system, which can be autonomously deployed.

Parameter, Value: Power: 1,000 kW

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.1 Lightweight Concepts

12.2.1.5 Precision, Expandable Structure

TECHNOLOGY

Technology Description: Deployable lightweight structures with high precision.

Technology Challenge: Precision position knowledge and control, and integral distributed actuation.

Technology State of the Art: 6.5 meter segmented mirror; James Webb Space Telescope is under development, with 18 segments that deploy but are not expandable.

Parameter, Value:	TRL
Mechanical and functional performance (including expandable size required) at low mass.	4

Technology Performance Goal: Application specific mechanical and functional performance (including expandable size required) at low mass.

Parameter, Value:	TRL
Meeting structural and functional requirements (mission specific).	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Large precision space structure.

Capability Description: Deployable structure with high precision; may offer a lightweight replacement for traditional pointing and alignment mechanisms.

Capability State of the Art: 14 meter mesh reflector antennas for radio frequency, and 2.4 non-expandable single objective optical mirrors.

Parameter, Value:

Aperture diameter – 14m (RF), 2.4m (optical)

Capability Performance Goal: Very large and precise surfaces for in-space collectors or reflectors.

Parameter, Value:

Aperture diameter – 50m (optical)

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Exoplanet Direct Imaging Mission	Enhancing	--	2030*	2025	5 years
Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enabling	--	2035*	2030	5 years
Strategic Missions: X-ray Surveyor Mission	Enabling	--	2035*	2030	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

12.2 Structures
12.2.1 Lightweight Concepts

12.2.1.6 Lander and Surface Habitat

TECHNOLOGY

Technology Description: Lander and habitat for crewed, long-duration planetary (or lunar) missions.

Technology Challenge: Develop inflatable and composite structure for long-term exposure to planetary environments providing for structural health monitoring including lead detection, isolation and repair, radiation protection, damage resistance or tolerance, and dust mitigation.

Technology State of the Art: Ground demo habitation modules.

Parameter, Value: Mechanical and functional performance at low mass: values vary depending on application.

TRL: 2

Technology Performance Goal: Mechanical and functional performance at low mass.

Parameter, Value: Meeting structural and functional requirements: values vary depending on application.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Lander and habitat for crewed, long-duration planetary (or lunar) missions.

Capability Description: Integrated structural system (for example, dust mitigation, radiation, permeability, thermal) for scientific and habitability requirements of a long-duration lunar or planetary mission. Viable habitable structural systems for a full set of mission requirements are essential for crewed missions and exploration.

Capability State of the Art: Non-integrated systems in Apollo, 3-day stay capability, and no radiation protection.

Parameter, Value: Percent SOA mass reduction from advanced concepts and integrated systems: 0 to 5%

Capability Performance Goal: Surface habitat for multi-year missions with reduced mass and/or expandabilty. High cycle and long-term environmental (for example, dust, atmosphere) tests are needed to verify durability and leakage. Integrated radiation protection solution for minimum mass.

Parameter, Value: Percent SOA mass reduction from advanced concepts and integrated systems: 20%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.2 Design and Certification Methods

12.2.2.1 Streamlined Design Analysis Cycle (DAC) Process

TECHNOLOGY

Technology Description: Streamlined and integrated analysis tool and process.

Technology Challenge: Software engineering for data interfaces from existing tools, integration of computational modules having varying levels of fidelity in the modeled physics, and including robust statistical margin and sensitivity analyses in a user friendly interface.

Technology State of the Art: An integrated environment exists and can be used as an example for the desired system.

Parameter, Value: Time to compute end-to-end loads and sizing for flight hardware.

TRL: 4

Technology Performance Goal: Time to compute end-to-end loads and sizing for flight hardware.

Parameter, Value: Reduction in cycle time by 50%.

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Reduced time to execute a design and analysis cycle for NASA flight hardware.

Capability Description: Integration of several design analysis cycle steps into a single software environment trimming months from the present process.

Capability State of the Art: Presently modeling, analyses, and diagnostic testing are not integrated.

Parameter, Value: Cycle for major integrated system: 12 months.

Capability Performance Goal: At least 50% reduction in cycle time.

Parameter, Value: Cycle for major integrated system: 6 months.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.2 Design and Certification Methods

12.2.2.2 Method for Composite Allowable Prediction

TECHNOLOGY

Technology Description: Improved methodology for composite design allowables.

Technology Challenge: Validation of progressive failure computational models by test. Developing validated statistical methods for fusing results from predictive models with results from experiments. Developing nondestructive evaluation (NDE) approaches that can detect and quantify defects in validation testing.

Technology State of the Art: A variety of failure models (both empirical and theoretical) exist but no comprehensive sizing architecture exists.

Parameter, Value:	**TRL**
Time and cost to integrate new composite materials into flight hardware.	3

Technology Performance Goal: Time and cost to integrate new composite materials into flight hardware.

Parameter, Value:	**TRL**
Reduction in time and cost: 50% reduction.	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Reduced time and cost to integrate new composites into flight hardware.

Capability Description: Design using composites requires allowables that are presently developed empirically from expensive building block tests which limits the design options that can be explored. This methodology will be a more cost effective capability using validated failure models, which will also result in mass savings through accessing a larger composite architecture design space.

Capability State of the Art: Presently allowables are purely empirically based using the results from many tests (~3,000) that are treated statistically according to standard approaches.

Parameter, Value:
Number of specimen tests for allowable database: 3,000

Capability Performance Goal: Significant reduction in testing requirements (at least 50%) for the same level of allowable reliability.

Parameter, Value:
Number of specimen tests for allowable database: 80% reduction.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.2 Design and Certification Methods

12.2.2.3 Probabilistic Design Methodology

TECHNOLOGY

Technology Description: Probabilistic methodology for structural design and certification.

Technology Challenge: Characterization of both random and non-random uncertainties from all stages of the design cycle and anticipated service life to create a statistically based method for design decisions for space systems.

Technology State of the Art: Basic theory is understood and some commercial software packages are available, but the practical use in design of aerospace structures is limited. (An industry study showed only small mass savings are possible when designed to lower reliability, greater mass saving are possible when incorporating NASA-required proof tests in reliability-based design.)

Parameter, Value: Methods have had limited use. Higher reliability designs can be generated, but little mass savings.

TRL: 5

Technology Performance Goal: Reliable mechanical performance at low mass; minimum risk statistics to guide development and certification test decisions for reducing costs.

Parameter, Value: Reduction in mass at quantified reliability; reduced development and certification test costs.

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Reduced risk to incorporate new materials or structural concepts into flight hardware.

Capability Description: Replacing heritage factor-of-safety design approaches with methodology that quantifies probability of failure to enable lighter weight designs with quantified reliability for non-heritage concepts. Design, development, test, and evaluation resource allocation decisions are based on the effect on reliability.

Capability State of the Art: Probabilistic techniques are not commonly used for aerospace.

Parameter, Value: Percent SOA mass reduction: 0 to 5%

Capability Performance Goal: Quantified reliability and mass savings.

Parameter, Value: Percent SOA mass reduction: 20%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.2 Design and Certification Methods

12.2.2.4 High-Fidelity Response Simulation

TECHNOLOGY

Technology Description: Fidelity of structural analysis tools.

Technology Challenge: Maturing computational models having the appropriate physics for the phenomena of interest. Development of high fidelity structural test data using improved measurement techniques for validation of models. Improving metrology methods to measure as-built geometry.

Technology State of the Art: Some current activities to develop high-fidelity response simulation, (for example, buckling of cylinders for launch vehicle design in shell buckling knockdown factor assessment).

Parameter, Value: Predictions using standard practices do not match tests (so designs use conservative heritage empirical correction factors).

TRL: 5

Technology Performance Goal: Accurate predictions of structural response and failure.

Parameter, Value: Predictions with accuracy sufficient for replacing physical tests at structural component scale (and no correction factors needed).

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Reduced cost and cycle time in development and qualification testing for flight hardware.

Capability Description: Using modeling and simulation as virtual testing to generate better information early in the design cycle which reduces reliance on costly development and qualification testing.

Capability State of the Art: Methodology not presently used for flight hardware.

Parameter, Value: Percent of reduction for SOA development cycle: 0%

Capability Performance Goal: Develop and implement a technology infusion plan to transfer high-fidelity simulation technologies to design and test engineers.

Parameter, Value: Percent of reduction for SOA development cycle: 30%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.2 Design and Certification Methods

12.2.2.5 Virtual Digital Certification Method

TECHNOLOGY

Technology Description: Analysis-based certification of structures.

Technology Challenge: Development of validated analysis tools integrated with uncertainty quantification and statistical tools to quantify probabilities of failure. Development of relevant criteria for certification.

Technology State of the Art: Ongoing efforts to incorporate realistic physics to improve reliability and ease of structural analysis techniques at NASA and elsewhere.

Parameter, Value: Some high fidelity analysis methods available, but not integrated in standard engineering processes.

TRL 2

Technology Performance Goal: Accurate predictions of structural response and failure available in standard engineering tools.

Parameter, Value: Predictions with accuracy sufficient for replacing physical tests in engineering design and certification processes.

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Reduced cost and cycle time in development and qualification testing for flight hardware.

Capability Description: Methodology for systematic validation and verification of models of pristine and degraded structure at all scales in the building block development pyramid to reduce costly physical testing and provide improved confidence for combined environments that cannot be simulated in test.

Capability State of the Art: Methodology not presently used for flight hardware.

Parameter, Value: Percent of reduction for SOA certification cycle: 0%

Capability Performance Goal: At least 30% reduction in cost and development time.

Parameter, Value: Percent of reduction for SOA certification cycle: 30%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.2 Design and Certification Methods

12.2.2.6 Landing Dynamics Prediction Method

TECHNOLOGY

Technology Description: Integrated analysis and design methodology for landing dynamics.

Technology Challenge: Analysis development at the component level through correlation with test data to characterize uncertainty and confidence of predictions.

Technology State of the Art: Landing dynamic analyses are currently performed at a number of NASA centers for various applications; some efforts are ongoing to better quantify uncertainties.

Parameter, Value:

Large uncertainty factors used in practice.

TRL: 4

Technology Performance Goal: Accurate predictions of loads and dynamic structural response; statistically based method for incorporation of prediction uncertainty.

Parameter, Value:

Elimination of uncertainty factors and development of predictions with accuracy sufficient for replacing physical tests for structural certification and that reduce mass from elimination of conservative assumptions.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Reduced costs and penalties from conservatism in predictions of load and dynamic structural response.

Capability Description: Implementing probabilistic techniques, identification of model validation metrics and verifiable requirements. Reduction of loads through active control during mission.

Capability State of the Art: Model calibration is a standard practice, but model validation for system qualification is not. Worst-on-worst cases and large uncertainty factors for loads are usually assumed.

Parameter, Value:

Percent of reductions from SOA cost for affected systems 0%;

Percent of reductions from SOA loads/mass for affected systems: 0%

Capability Performance Goal: At least 50% reduction in development and qualification costs though reduction in large scale testing, with 30% reduction in loads and mass.

Parameter, Value:

Percent of reductions from SOA cost for affected systems: 50%;

Percent of reductions from SOA loads/mass for affected systems: 30%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.2 Design and Certification Methods

12.2.2.7 Virtual Digital Fleet Leader Certification Methods

TECHNOLOGY

Technology Description: Integrated analysis, design, and structure sustainment methodology.

Technology Challenge: Integration of high-fidelity and certification models, service life inspection, and health monitoring assessment data, and life extension prediction methods in a real-time framework.

Technology State of the Art: See TA 12.2.2.5 Virtual Digital Certification for mechanics SOA. Full field nondestructive evaluation (NDE) for material state used for small areas. Statistical techniques for data analysis and fusion developed, but not scaled up.

Parameter, Value:	TRL
Methodology at very low maturity	1

Technology Performance Goal: Autonomous predictions of structural response and margin for both as-built and degraded structure.

Parameter, Value:	TRL
Predictions with accuracy sufficient for mission decision-making.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Design and effective sustainment of deep space structural system over its mission life.

Capability Description: The use of a detailed digital mock-up (integration of high-fidelity and certification models, service life inspection and health monitoring assessment data, and life extension prediction methods) of an as-built aircraft or flight vehicle to certify continued safe operation of the vehicle.

Capability State of the Art: Methodology not presently used for flight hardware.

Parameter, Value:

Percent of reductions from SOA cost for affected systems 0%;

Percent of reductions from SOA loads/mass for affected systems: 0%

Capability Performance Goal: At least 50% reduction in development and qualification costs through reduction in large scale testing, and 30% reduction in loads and mass for structure; critical to sustainment in deep space.

Parameter, Value:

Percent of reductions from SOA cost for affected systems 50%;

Percent of reductions from SOA loads/mass for affected systems: 30%;

Sustainment benefits are not easily quantified.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.3 Reliability and Sustainment

12.2.3.1 Predictive Damage Method

TECHNOLOGY

Technology Description: Experimental method of damage progression for modeling predictive design allowables, accurate simulation of damage initiation and propagation with significantly reduced testing schedule and cost.

Technology Challenge: Need to get past limited physics-based models where much empiricism in damage and failure theories predicate significant testing or conservative design.

Technology State of the Art: High degree of empiricism in damage and failure theories necessitates limiting design space because of significant testing requirements. Limited physics-based damage models that are computationally expensive.

Parameter, Value:

High confidence in modeling capability for material defects.

TRL: 3

Technology Performance Goal: Development and validation of physics-based capabilities (for example, open-hole tension and compression models for general laminates).

Parameter, Value:

High confidence in modeling capability for material defects.

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Development and validation of physics-based capabilities (for example, open-hole tension and compression models for general laminates).

CAPABILITY

Needed Capability: Damage prediction math model.

Capability Description: Enable the designer to visualize internal damage for structural life assessment.

Capability State of the Art: A high degree of empiricism in damage and failure theories prevents the accurate extension into relevant environments in non-metallics.

Parameter, Value:

Confidence in modeling capability for material defects in non-metals is low and covered by additional conservatism to address uncertainties.

Capability Performance Goal: Development and validation of physics-based capabilities (for example, open-hole tension and compression models for general laminates).

Parameter, Value:

High confidence in modeling capability for material defects.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.3 Reliability and Sustainment

12.2.3.2 Life-Extension Prediction Method

TECHNOLOGY

Technology Description: Capability to model the integrity of a structure at any time in its life to assess the remaining life based upon the actual flight history (beyond the design environment).

Technology Challenge: Develop, correlate, and validate life prediction models for deep space vehicle materials and structures in relevant environments.

Technology State of the Art: Models exist for terrestrial environments (metals).

Parameter, Value: Accuracy of correlation for failure modes in metallic structures.

TRL: 2

Technology Performance Goal: Correlated life models of deep space structures (including composites) in space environments.

Parameter, Value: Accuracy of correlation for composites.

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: In flight data acquisition and embedded sensor development.

CAPABILITY

Needed Capability: In-situ structural life assessment.

Capability Description: Correlated capability for metals, in development for polymer matrix composites and ceramics.

Capability State of the Art: Working system for metals in Earth's environments. Some test data for non-metallic material characterization in lab environments.

Parameter, Value: Confidence in modeling capability for material defects is low.

Capability Performance Goal: Need to develop and correlate models to environmental durability test data.

Parameter, Value: High confidence in modeling capability for material defects.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.3 Reliability and Sustainment

12.2.3.3 Structural Health Monitoring and Thermal Health Monitoring (SHM/THM) System Integration

TECHNOLOGY

Technology Description: Data acquisition system with distributed sensors to report environmental and structural integrity information.

Technology Challenge: Development of lightweight sensors and installation techniques; antennas and power sources for wireless systems; and supporting data acquisition systems and techniques.

Technology State of the Art: Varies with structural health monitoring (SHM) and thermal health monitoring (THM) measurement technique. However, some work has been accomplished for interwoven fiberoptics (graphite layups), nano based resins, and piezoelectrics.

Parameter, Value: | **TRL**
Correlation of transmitted signal to the event. | 2

Technology Performance Goal: Reliably sense, and transmit strain, temperature, spectral harmonics, and impact.

Parameter, Value: | **TRL**
Correlation of transmitted signal to the event. | 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: In-flight data acquisition and embedded sensor development.

CAPABILITY

Needed Capability: Smart structure.

Capability Description: In flight structural monitoring provides beneficial weight, cost, and schedule impacts; validation of environmental and structural models; and monitoring life and safety.

Capability State of the Art: Varies with SHM and THM measurement technique. Other government agency fleet maintenance has made some progress in atmospheric environments.

Parameter, Value:
Limited area monitoring with little integration across sensor systems: 15%

Capability Performance Goal: Development and demonstration of practical system for large area monitoring in a space environment.

Parameter, Value:
Development and demonstration of practical system for large area (full vehicle) monitoring: 100%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.3 Reliability and Sustainment

12.2.3.4 In-Situ Structural / Thermal Assessment Model

TECHNOLOGY

Technology Description: Integrated mathematical modeling capability to interpret the structural and thermal sensor output.

Technology Challenge: Need damage data and/or modeling results as well as realistic testing and validation in a relevant environment.

Technology State of the Art: Preliminary work for other government agency fleet management has shown promise.

Parameter, Value: Accuracy of event correlation.

TRL 3

Technology Performance Goal: Reliably to remotely interpret strain, temperature, spectral harmonics, and impact events.

Parameter, Value: Accuracy of event correlation.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Structural and thermal health monitoring systems, and structure or thermal response modeling and control algorithms validation.

CAPABILITY

Needed Capability: In-flight structural integrity assessment.

Capability Description: Assess structural integrity throughout manufacturing, launch, and deep space missions to the end of service life.

Capability State of the Art: Difficult to determine the location, magnitude, and type of damage from sensors. Present solutions are prone to instability and non-convergence.

Parameter, Value:
Obtain nondestructive evaluation (NDE) capability from monitoring sensors: 5 to 10%

Capability Performance Goal: Benchmarking of inverse methodology to additional damage data. Realistic testing in a relevant environment. To facilitate detection and characterization of damage during testing and service.

Parameter, Value:
Remote determination of extent of damage and residual capability determination: 95%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.3 Reliability and Sustainment

12.2.3.5 Autonomous In-Situ Structural / Thermal Repair System

TECHNOLOGY

Technology Description: Integrated capability to interpret structural anomalies and effect repairs.

Technology Challenge: Develop repair and validation capability for restoration of structural or thermal protection integrity in space.

Technology State of the Art: Limited repair kits for extravehicular activity (EVA) repair of pressure leaks of space station modules and Shuttle thermal protection system (TPS).

Parameter, Value:	TRL
Repair efficiency without parts from Earth.	1

Technology Performance Goal: Analyze and design repair with minimal earth involvement.

Parameter, Value:	TRL
Repair efficiency without parts from Earth.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Structural health monitoring systems, structure response modeling and control algorithms validation, deep space EVA and autonomous structural preparation and repair.

CAPABILITY

Needed Capability: Autonomous structural assessment and repair.

Capability Description: Enable structural repair in deep space when Earth-based assessment and repair are not timely for crew survival or mission success..

Capability State of the Art: Limited repair kits for EVA repair of pressure leaks of space station modules and Shuttle TPS, mostly non-structural.

Parameter, Value:

Assessment transmitted from Earth, human touch repair: 3%

Capability Performance Goal: Integrated remote (deep space) monitoring, assessment, and repair capability.

Parameter, Value:

Robustness and autonomy in structural assessment and repair: 80%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.3 Reliability and Sustainment

12.2.3.6 Virtual Digital Fleet Leader Sustainment

TECHNOLOGY

Technology Description: Integrated high-fidelity certification models, service life inspection and health monitoring assessment data, and life extension prediction methods with test tools and methods.

Technology Challenge: Integrate constituent capabilities in various stages of development to manage vehicle integrity through its life cycle.

Technology State of the Art: Digital twin is in concept stage, but constituent capabilities in various stages of development.

Parameter, Value: Confidence in sensor interpretation, and in integrated prediction accuracy.

TRL: 1

Technology Performance Goal: Ability to adjust life prediction based upon the monitored past, the current structural status, and the potential new environments coming in the vehicle life.

Parameter, Value: Confidence in sensor interpretation, and in integrated prediction accuracy.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Demonstration of fusion of preliminary capabilities from the constituent capabilities.

CAPABILITY

Needed Capability: Digital twin.

Capability Description: Create an ‘as-built’ structural model of each deep space structure to assess structural integrity and remaining structural life. Provide safety of the structural system to support mission decisions for operation or repair.

Capability State of the Art: Digital twin is in concept stage, but constituent capabilities are in various stages of development.

Parameter, Value:
Depends on component (sensors, models, in-situ capability, etc.), but it is a low 3%.

Capability Performance Goal: Demonstration of fusion preliminary capabilities in several of the constituent capabilities.

Parameter, Value:
Depends on component (sensors, models, in-situ capability, etc.).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.4 Test Tools and Methods

12.2.4.1 Integrated Flight Test Data Identification Model

TECHNOLOGY

Technology Description: Analytical model correlation of flight data for model certification and structural certification.

Technology Challenge: Develop prototype process that incorporates data acquisition and model correlation with full-scale flight test.

Technology State of the Art: Currently performed somewhat inadequately as an integrated technology level.

Parameter, Value: Model validation with flight environments.

TRL 3

Technology Performance Goal: Incorporate flight test data into certification via physics based model correlation.

Parameter, Value: Model validation with flight environments.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Structural health monitoring systems, structure response modeling, and control algorithms validation.

CAPABILITY

Needed Capability: Incorporate flight test into certification.

Capability Description: Takes advantage of flight testing to enable more efficient (in terms of time and cost) structural certification.

Capability State of the Art: Currently performed somewhat inadequately as an integrated technology level.

Parameter, Value: Certification focused on qual test article.

Capability Performance Goal: Develop prototype process that incorporates data acquisition and model correlation with full-scale flight test.

Parameter, Value: Certification focused certified models and on each flight vehicle's monitored performance, as well as qualification testing.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.4 Test Tools and Methods

12.2.4.2 Full-Field Data Acquisition System

TECHNOLOGY

Technology Description: Far field and integral structural sensor systems for point and global measurements.

Technology Challenge: Implementation existing far field technology and structural health monitoring (SHM) development on a much larger scale (static and dynamic).

Technology State of the Art: Used on small-scale tests, but not yet demonstrated on full vehicle scale.

Parameter, Value:	TRL
Fidelity and completeness of data.	3

Technology Performance Goal: Data acquisition to obtain full structural responses on full-scale vehicles.

Parameter, Value:	TRL
Incorporation and use of health monitoring into data for structural certification.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Structure response modeling and control algorithms validation.

CAPABILITY

Needed Capability: Integrated remote structural test data.

Capability Description: Provides Instrumentation and test data for certification without the time and cost of instrument installation and calibration.

Capability State of the Art: Used on small-scale tests, but not yet demonstrated on full vehicle scale.

Parameter, Value:

Multiple physical measurements on full-scale articles.

Capability Performance Goal: Implement existing technology on a much larger scale (static and dynamic).

Parameter, Value:

Multiple physical measurements on full-scale articles in ground and flight conditions.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.4 Test Tools and Methods

12.2.4.3 Full-Field Model Verification and Validation Model and System

TECHNOLOGY

Technology Description: Testing and correlation capability to enable verification and validation for full scale, full field analytical models, test hardware, instrumentation, data acquisition, and data reduction.

Technology Challenge: Develop prototype model correlation process that incorporates full field data.

Technology State of the Art: This is an improvement on a process that is currently not well performed or integrated in the NASA human flight certification process.

Parameter, Value:

Cost, schedule, and mass reduction starting at the certification process.

TRL 2

Technology Performance Goal: Uncertainty reduction from accurate model correlation of as-built full-scale vehicles in laboratory and flight environments.

Parameter, Value:

Cost, schedule, and mass reduction starting at the certification process.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Structural health monitoring systems, structure response modeling, and control algorithms validation.

CAPABILITY

Needed Capability: Model and hardware verification from full field data acquisition.

Capability Description: This capability provides better correlated models for lower cost vehicle certification as well as improved understanding of vehicle performance modeling for comparison with flight test instrumentation.

Capability State of the Art: Used on small-scale tests, not yet demonstrated on full vehicle scale.

Parameter, Value:

Verification and validation of multiple physical measurements on full scale articles.

Capability Performance Goal: Develop prototype model correlation process that incorporates full field data.

Parameter, Value:

Verification and validation of multiple physical measurements on full scale articles in ground and flight conditions.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.4 Test Tools and Methods

12.2.4.4 Virtual Digital Certification Method and System

TECHNOLOGY

Technology Description: Precursor to the Virtual Digital Fleet Leader capability. Here, test methods would be created for correlation across the building block spectrum, engaging the available structural health monitoring and thermal health monitoring capabilities to address the full life cycle of a space vehicle.

Technology Challenge: Develop test methods for systematic verification and validation of models of pristine and degraded structure at all scales in the building block development pyramid with design certification methods.

Technology State of the Art: Certification by analysis is lacking, especially in large-scale configurations.

Parameter, Value: Confidence in data and model correlation.

TRL: 2

Technology Performance Goal: Incorporate onboard sensors and as built models into the certification process for laboratory and flight environments.

Parameter, Value: Confidence in data and model correlation.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Structural health monitoring systems, structure response modeling, and control algorithms validation.

CAPABILITY

Needed Capability: Certification of smart structure.

Capability Description: This capability enables certification of structures with integrated sensor systems from the cyber manufacturing and assembly, though approval for flight and to the end of mission life. The result is both a higher knowledge of the structural integrity, and a faster and cheaper design cycle.

Capability State of the Art: Certification by analysis is lacking, especially in large-scale configurations.

Parameter, Value: Better capability to certify by analysis and verify by test on full-scale test and flight vehicles.

Capability Performance Goal: Once the specific application is defined, test methods at the component to larger scales of the building block pyramid should be developed.

Parameter, Value: Better capability to certify by analysis and verify by test.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.4 Test Tools and Methods

12.2.4.5 Virtual Digital Fleet Leader Testing

TECHNOLOGY

Technology Description: This represents the testing and model correlation portion of the virtual fleet leader to better understand vehicle life in the design phase for real time adjustment to the vehicle life during its mission.

Technology Challenge: Demonstration of fusion of preliminary capabilities in several of the constituent capabilities.

Technology State of the Art: This work has been performed in a limited, high effort for the return, basis on the International Space Station (ISS).

Parameter, Value:
Confidence in structural data and model correlation.

TRL: 1

Technology Performance Goal: Continually know the structural status of in-flight vehicles and be able to model future loads assessments for life prediction throughout mission life cycle.

Parameter, Value:
Confidence in structural data and model correlation.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Structural health monitoring systems, structure response modeling, and control algorithms validation.

CAPABILITY

Needed Capability: Digital twin.

Capability Description: Provides a continuing certification capability throughout the mission or service life of a deep space structure. It enables the needed robustness and autonomy for deep space travel.

Capability State of the Art: This work has been performed in a limited, high level of effort for the return, basis on the ISS.

Parameter, Value:
Better capability to certify by analysis and verify by test on full scale test and flight vehicles.

Capability Performance Goal: Demonstration of fusion preliminary capabilities in several of the constituent capabilities.

Parameter, Value:
Better capability to certify by analysis and verify by test.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.5 Innovative, Multifunctional Concepts

12.2.5.1 Multifunctional Cryo-Tank

TECHNOLOGY

Technology Description: Cryo-tanks designs based on integrated insulation, structural, and sensor elements.

Technology Challenge: Address competing thermal isolation and strength or stiffness issues. Integrating primary load paths (especially at joints). Cryotank and sensor integration.

Technology State of the Art: NASA Composite Cryo Tank project has integrated composite structure. Other composite tanks with integrated sensors have been tested at NASA facilities.

Parameter, Value:
Integration percentage: 33%

TRL
4

Technology Performance Goal: Provide integrated insulation, structure, and sensor design elements based on materials, analyses, manufacturing, and sensors shown to meet cryo-tank system requirements

Parameter, Value:
Integration percentage: 80% with 30% mass reduction and meeting performance of non-integrated structures.

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Multifunctional materials and processes, material properties allowables, sensors, and analyses tools correlated to test hardware.

CAPABILITY

Needed Capability: Highly integrated cryo-tank structures.

Capability Description: Provide integrated insulation, structure, and sensors design elements based on materials, analyses, manufacturing, and sensors for cryo-tank structures.

Capability State of the Art: Launch vehicle cryo-tanks have integrated structural components and little else. All but one has been metallic.

Parameter, Value:
Integration percentage: 33% with mass comparable to existing cryo-tanks.

Capability Performance Goal: Integrated structural and insulation, component, and performance monitoring sensors with reduced system mass and simplified integration compared to non-integrated cryo-tank systems.

Parameter, Value:
Integration percentage: 80% with mass reduction of 30% compared to existing cryo-tanks.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.5 Innovative, Multifunctional Concepts

12.2.5.2 Multifunctional Pressurized Structure

TECHNOLOGY

Technology Description: Pressurized structure designs with integrated micro-meteoroid orbital debris, radiation, and permeability protection, electrical harnessing, thermal control, and sensor subsystems.

Technology Challenge: Address competing system requirements. Integrating primary load paths (especially at joints).

Technology State of the Art: Composite Crew Module used composite materials and processes shown to hold relevant pressure.

Parameter, Value:
Integration percentage: 20%

TRL 3

Technology Performance Goal: Provide integrated structure, insulation, sensors, harnessing, and protective subsystems design elements based on materials, analyses, manufacturing, and sensors for pressurized structures while meeting system requirements for a safe and reliable human environment.

Parameter, Value:
Achieve pressure vessel structural reliability for safe human environment for space missions.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Multifunctional materials and processes, material properties allowables for structures with integrate subsystem components, sensors, and harnesses. Analyses tools correlated to test hardware.

CAPABILITY

Needed Capability: Multifunctional elements for pressurized structures.

Capability Description: Provide integrated micro-meteoroid orbital debris, radiation, and permeability protection and thermal control element designs for pressurized structures for manned habitation in space environments.

Capability State of the Art: Pressurized structures have independent micro-meteoroid orbital debris, radiation, and permeability protection and independent harnessing and thermal controls attached to structures.

Parameter, Value:
Integration percentage: 20%

Capability Performance Goal: Integrated protective sub-systems elements, harnessing and thermal control in pressurized structure for a safe human environment.

Parameter, Value:
Integration percentage: 60% with mass reduction of 30% compared to unintegrated habitable pressurized structures.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.5 Innovative, Multifunctional Concepts

12.2.5.3 Multifunctional Non-Pressurized Structure

TECHNOLOGY

Technology Description: Non-pressurized structure designs with integrated micro-meteoroid orbital debris and radiation protection, thermal control capability, electrical harnessing, and sensor subsystems.

Technology Challenge: Multifunctional materials and processes, material properties allowables integrate subsystem components, sensors, and harnesses. Analyses tools correlated to test hardware.

Technology State of the Art: Single combination design, (e.g., structures with integrated thermal elements, or impact resistant structures, or radiation hardening, etc.) are being developed.

Parameter, Value:
Integration percentage: 15%

TRL 2

Technology Performance Goal: Integrated structure, insulation, sensors, harnessing, and protective subsystems design elements based on materials, analyses, manufacturing, and sensors for non-pressurized structures.

Parameter, Value:
Integration percentage: 60% with mass reduction of 30% compared to unintegrated non-pressurized structures.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Multifunctional materials and processes, material properties allowables for structures with integrate subsystem components, sensors, and harnesses. Analyses tools correlated to test hardware.

CAPABILITY

Needed Capability: Multifunctional elements for non-pressurized structures.

Capability Description: Provide integrated micro-meteoroid orbital debris and radiation protection and thermal control element designs for non-pressurized structure for space environments.

Capability State of the Art: Structures with integrated harnessing, and thermal control and sensors have been developed.

Parameter, Value:
Integration percentage: 15%

Capability Performance Goal: Fully integrated non-pressurized structure protective sub-systems elements with reduced system mass and simplified integration compared to non-integrated non-pressurized structure.

Parameter, Value:
Integration percentage: 60% with mass reduction of 30% compared to unintegrated non-pressurized structures.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.5 Innovative, Multifunctional Concepts

12.2.5.4 Reusable Modular Component

TECHNOLOGY

Technology Description: Structure design with components for multiple purposes and multiple uses.

Technology Challenge: Modular design without undue weight penalties.

Technology State of the Art: Solid rocket motors are reusable in same environment. Aircraft with wings that change shape and position for different flight environments.

Parameter, Value:

Structures that meet multiple mission uses.

TRL
5

Technology Performance Goal: Structures that can readily change to meet multiple mission profiles and multiple mission uses.

Parameter, Value:

Achieve structural performance requirements for multiple mission system requirements.

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Description of mission requirements and knowledge of number of reuse cycles.

CAPABILITY

Needed Capability: Reusable structures and repurposed structures that are employed with shorter cycle times.

Capability Description: Structures that can be reused or reconfigured for use across multiple mission profiles and systems.

Capability State of the Art: Solid rocket motors are reusable in same environment. Aircraft with wings that change shape and position for different flight environments.

Parameter, Value:

Structures that meet multiple mission uses or are reuseable with reduced cycle time than completing new designs.

Capability Performance Goal: Structures that meet multiple mission profiles and multiple mission uses.

Parameter, Value:

Achieve structural performance requirements for multiple mission system requirements with reduced cycle time reduction of 50%.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015 - 2021	5 years

12.2 Structures
12.2.5 Innovative, Multifunctional Concepts

12.2.5.5 Integrated Window

TECHNOLOGY

Technology Description: Provide integrated window and structure design that enables proper sealing, strength, and reparability for space application.

Technology Challenge: Materials for long-term space environment and integration of windows system into structure.

Technology State of the Art: Bonded windows into demonstrator.

Parameter, Value: | **TRL**
Number of parts and processes, mass, and window leak rate. | 3

Technology Performance Goal: Window in human-rated vehicles with the required sealing and mechanical requirements (strength, stiffness, etc.).

Parameter, Value: | **TRL**
Approach the capabilities of window frames bolted in structures (strength, stiffness, sealing, etc.). | 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Reliable and robust bonded window development.

CAPABILITY

Needed Capability: Low mass window mounts connecting structure to windows for habitable space structures.

Capability Description: Window mounts connecting structure to windows that seal and take loads in habitable space-based structures.

Capability State of the Art: Windows are currently attached to a frame and sealed to an o-ring by bolt clamping force.

Parameter, Value:
Number of parts and processes, mass, and window leak rate.

Capability Performance Goal: Integrated window, seal, and frame providing a strong and stiff structural load path, and pressure seal, with minimum number of parts and processes.

Parameter, Value:
Number of parts and processes, mass, and window leak rate.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

12.2 Structures
12.2.5 Innovative, Multifunctional Concepts

12.2.5.6 Active Control of Structural Response Model

TECHNOLOGY

Technology Description: Structure designs with active controls to optimize structure performance.

Technology Challenge: Accurately modeling full-scale structures. Structural health monitoring in all the right places. Providing controls without adding undue weight.

Technology State of the Art: Piezoelectric and phase change materials in devices.

Parameter, Value: TRL 2

Change in performance depends on operating envelope (i.e., mechanical shape change, physical property change, etc.).

Technology Performance Goal: Structure performance within performance envelope with little mass and power change.

Parameter, Value: TRL 6

Meet all design requirements in any response regime.

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Structural health monitoring systems, structure response modeling, and control algorithms validation.

CAPABILITY

Needed Capability: Active structure control.

Capability Description: Provides structural system designs with adjustable structure response within the design envelope and outside nominal conditions.

Capability State of the Art: Structures that change physical characteristics with active manipulation to respond to its operating environment.

Parameter, Value:

Change in performance depends on system feedback.

Capability Performance Goal: Structure performance change affected by design with manual inputs, while maintaining fundamental structure requirements.

Parameter, Value:

Meet all design requirements with no added mass.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: X-ray Surveyor Mission	Enhancing	--	2035*	2030	5 years
Earth Systematic Missions: Geostationary Coastal and Air Pollution Events (GEO-CAPE)	Enhancing	--	2024*	2019	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

12.2 Structures
12.2.5 Innovative, Multifunctional Concepts

12.2.5.7 Integrated Adaptive

TECHNOLOGY

Technology Description: Structural systems that possess the inherent capability to change mechanical and functional performance in-flight.

Technology Challenge: Intergrating structure designs and controls based on interpretation of realtime inputs (i.e., from structural health monitoring) for multiple operating environments and structures types.

Technology State of the Art: Passive structural controls using piezoelectric materials.

Parameter, Value: Mechanical and functional performance at low mass and little power.

TRL: 1

Technology Performance Goal: Structure performance within performance envelope with little mass and power change.

Parameter, Value: Mechanical and functional performance at low mass and little power.

TRL: 5

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Data acquisition and embeded sensor development.

CAPABILITY

Needed Capability: Structural systems to autonomously modify mechanical and/or functional (i.e., thermal) performance with little mass or power.

Capability Description: Provide structures systems that self-sense performance parameters, evaluate if structural and/or functional performance is within operating envelope and adjust, without mission commands, to maintain optimal performance or bring into an acceptable operational performance envelope.

Capability State of the Art: None in space, but some aeronautics use.

Parameter, Value:
Testbed system performance mass and power.

Capability Performance Goal: The integration of various existing SOA technologies, benchmarking of current capabilities, and identification of gaps using critical flight components as testbeds. The near-term product would be actively-controlled structures within mission phases to limit loads allowing for reducing structural mass in the design.

Parameter, Value:
Testbed system performance improvement: 20%; Mass and power change: 30%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: X-Ray Surveyor Mission	Enabling	--	2035*	2030	5 years
Earth Systematic Missions: Geostationary Coastal and Air Pollution Events (GEO-CAPE)	Enabling	--	2024*	2019	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

12.2 Structures
12.2.6 Loads and Environments

12.2.6.1 Combined Environments Modeling Tool

TECHNOLOGY

Technology Description: Tool that integrates the environmental loading of a structure to reduce uncertainties in the interactions.

Technology Challenge: Addressing multiple, competing, and transient environments. Data acquisition sensor development.

Technology State of the Art: Limited to moderate stochastic and time consistent assessment, completed by amount of uncertainty.

Parameter, Value: Uncertainty quantification.

TRL: 2

Technology Performance Goal: Accurate stochastic and time consistent assessment through all phases of a deep space mission.

Parameter, Value: Uncertainty quantification.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Data acquisition sensor development, and the interpretation of the structural responses.

CAPABILITY

Needed Capability: Modeling the full combined environmental structural response for efficient design.

Capability Description: More precise analytical models of the vehicle. More efficient design and analysis cycles (cost and schedule). Probabilistic design.

Capability State of the Art: High potential for ‘low-hanging fruit’ improvements for integration with current data acquisition and modeling capabilities.

Parameter, Value: Statistical uncertainty quantification.

Capability Performance Goal: Addressing multiple, competing, and transient environments. Data acquisition sensor development.

Parameter, Value: Statistical uncertainty quantification.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.6 Loads and Environments

12.2.6.2 Improved Method for Accurate Local and Global Loads and Environments

TECHNOLOGY

Technology Description: Method that reduces the environmental loading of a structure to the local load of a structural part (primary or secondary) to reduce uncertainties in process.

Technology Challenge: Modeling the effect of multiple, competing, and transient environments. Probabilistic and time consistency modeling and data acquisition sensor correlation.

Technology State of the Art: Moderate statistical incorporation of flight data through loads analyses and into detailed structural margin calculations.

Parameter, Value:
Conservatism in model uncertainty.

TRL 2

Technology Performance Goal: Time consistent and precise incorporation of mission loads into correlated physics-based models of all detailed parts of a deep space vehicle.

Parameter, Value:
Conservatism in model uncertainty.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Development of statistically-based design.

CAPABILITY

Needed Capability: More precisely reducing the global environment into a local design load.

Capability Description: More precise analytical models of the vehicle. More efficient design and analysis cycles (cost and schedule). Probabilistic design.

Capability State of the Art: High potential for 'low-hanging fruit' improvements for integration with current data acquisition and modeling capabilities.

Parameter, Value:
Incorporation of design, test, and manufacturing tools for cost efficient certification at lower mass.

Capability Performance Goal: Effective certification of detailed parts based upon as built dimensions, time consistent loading, and physics-based models.

Parameter, Value:
Incorporation of design, test, and manufacturing tools for cost efficient certification at lower mass.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.6 Loads and Environments

12.2.6.3 Test Validation Model

TECHNOLOGY

Technology Description: Model and test correlation of multiple, competing, and transient load environments for aerovehicles, launch vehicles, and planetary descent vehicles.

Technology Challenge: Modeling the effect of multiple, competing, and transient environments. Capture of relevant transient loads environments. Data acquisition and sensor development. Developing a range of prediction methodologies for launch, max-q and transonic fluctuating-pressure environments, including plume and plume-impingement effects. Improve fluid-structural coupling models.

Technology State of the Art: Historical subscale and local loads modeling used for design.

Parameter, Value:

Load model confidence.

TRL

2

Technology Performance Goal: Improve environmental load predictions of full-scale vehicle for reduced uncertainty.

Parameter, Value:

Load model confidence.

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Data acquisition and sensor development.

CAPABILITY

Needed Capability: Testing of combined and transient environments for structural efficiency.

Capability Description: Reduce uncertainty and structural conservatism via more precise model certification. Higher fidelity analytical models of the vehicle.

Capability State of the Art: Historical subscale and local loads modeling used for design.

Parameter, Value:

Load model confidence.

Capability Performance Goal: Improve environmental load predictions of full-scale vehicle for reduced uncertainty.

Parameter, Value:

Load model confidence.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.6 Loads and Environments

12.2.6.4 Design for Monitoring Strategy

TECHNOLOGY

Technology Description: Structural monitoring that enables more efficient design, including certification updates during a mission, autonomous assessment, and repair.

Technology Challenge: Model and test correlation of multiple, competing, and transient environments.

Technology State of the Art: A reasonably mature set of monitoring technologies exist, designs are at various incidental levels of compatibility, but structural systems have not been designed for monitoring.

Parameter, Value:	TRL
Compatibility of structural system and attendant monitoring systems	2

Technology Performance Goal: Integrated sensor systems designs that are compatible (impedance, noise, sensitivity, etc.) with the attendant structural systems designs for structural health and life cycle monitoring and management.

Parameter, Value:	TRL
Compatibility of structural system and attendant monitoring systems	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Development of component level designs with integrated sensor systems.

CAPABILITY

Needed Capability: Design and integration of future sensor technologies.

Capability Description: Adaptive structure, structural life updates during the mission, and autonomous, in-flight mitigation strategies.

Capability State of the Art: Integration as conceived has not been performed.

Parameter, Value:
Compatibility of structural system and attendant monitoring systems

Capability Performance Goal: Develop an efficient structure with efficiently integrated sensors for monitoring structural health in deep space.

Parameter, Value:
Compatibility of structural system and attendant monitoring systems

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.6 Loads and Environments

12.2.6.5 Mission Loads and Environments Monitoring

TECHNOLOGY

Technology Description: In-flight loads monitoring that enables the transition from design loads to actual mission loads and exact local structural response. Structural life assessment based upon flight history and updated predictions. Reliable measurement and acquisition of surface fluctuating pressures and corresponding structural responses on large scale flight vehicles (also applicable to wind tunnel models).

Technology Challenge: Design and integration of future sensor technologies. Lightweight, low-cost, low-risk flight data system suitable for use on production vehicles and models to create a database of pressures and structural responses for nominal and off-nominal flight conditions. Within a given class of vehicles, such a database could be used to refine loads mitigation approaches over the life of the vehicle class to improve operational efficiency.

Technology State of the Art: ~5% scale wind tunnel models tested under steady and unsteady conditions. No real-time mission loads available.

Parameter, Value: Data acquired in dynamic conditions relevant to flight; most testing done under steady conditions.

TRL: 2

Technology Performance Goal: Extensive flight data from real vehicles in a dynamic environment to provide validation and verification data for model refinement, and to provide data to evaluate structural health and life.

Parameter, Value: Varies. For example, surface fluctuating pressures measured in nominal ascent flight conditions covered by database: 100%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Embedded Sensor Development, Structural Health Monitoring, and Digital Twin technologies.

CAPABILITY

Needed Capability: Environments monitoring for precise in-flight loads development. Correlated surface fluctuating pressures and corresponding vibration response data from the vehicle's structure is needed for verified vibroacoustic models, and to design vehicles with maximum weight efficiency. Collection of surface pressure data from every flight would reduce uncertainty and reduce unneeded conservatism in vehicle structures. Initially, the data would be used for model development, verification, and validation; subsequent use could provide digital twin data for re-usable vehicles.

Capability Description: Post-launch improved math models. Adaptive Structure. Structural life updates during the mission. Autonomous, in-flight mitigation strategies.

Capability State of the Art: Custom designed sensor and acquisition system for each vehicle; removed after launch system verification. Integration as conceived has not been performed.

Parameter, Value: Data bandwidth and unit cost.

Capability Performance Goal: An off-the-shelf sensor and acquisition system with stick-on surface pressure sensors, accelerometers, and wireless integration with dramatically reduced telemetry requirements.

Parameter, Value: Reduce unit cost by factor of 10 for same data bandwidth.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.2 Structures
12.2.6 Loads and Environments

12.2.6.6 Autonomous In-Flight Mitigation Strategy

TECHNOLOGY

Technology Description: Strategies that enable real-time adjustments within a structural system to mitigate structural anomalies in various mission phases based upon flight history and updated predictions. Strategies may apply to static and dynamic structural loads to mitigate failure, fatigue, and/or control-structures interactions; or they may apply to mitigation of structural vibration and interior acoustic load (for example, during launch and ascent) using efficient adaptive and active technologies.

Technology Challenge: Environments monitoring for precise in-flight loads development, and developing robust, compact, weight-efficient mitigation approaches, including active and adaptive, that can be integrated into a lightweight structure.

Technology State of the Art: Some examples for launch acoustics include mass dampers, and Helmholtz resonators in fairings.

Parameter, Value: Time, precision, and/or mass efficiency in detection through mitigation.

TRL: 1

Technology Performance Goal: Reduce weight and improve effectiveness of mitigation treatments.

Parameter, Value: Time, precision, and/or mass efficiency in detection through mitigation.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Embedded Sensor Development, Structural Health Monitoring, and Digital Twin technologies.

CAPABILITY

Needed Capability: Autonomous, in-flight structural margin and life assessment and mitigation of detected degradation and damage. Reduce the weight penalty and improve effectiveness associated with vibroacoustic load mitigation strategies.

Capability Description: Mitigation strategies and treatments along with the detailed modeling and multi-disciplinary design capabilities that enable autonomous and safe accommodation of structural and environmentally induced load anomalies via use of structural and environmental monitoring.

Capability State of the Art: Integration as conceived has not been performed though some component capabilities exist (for example, piezoelectric actuators; numerical models at component level).

Parameter, Value: Time, precision, and/or mass efficiency in detection through mitigation.

Capability Performance Goal: Applicable mitigation treatments and the numerical models for assessing vehicle-level performance of a mitigation treatment. Integrated, multifunctional structural concepts that meet primary structural requirements plus provide mitigation.

Parameter, Value: Time, precision, and/or mass efficiency in detection through mitigation.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.3 Mechanical Systems
12.3.1 Deployables, Docking, and Interfaces

12.3.1.1 Common Universal Interchangeable Interface

TECHNOLOGY

Technology Description: Interface that will cost effectively and more reliably streamline system and spacecraft connectivity.

Technology Challenge: Main technology challenge is developing docking load attenuation and structural latching system that is compatible with international docking system interface commonality agreements while minimizing mass and cost impacts to NASA beyond-Earth orbit spacecraft and missions.

Technology State of the Art: NASA, U.S. commercial space companies, and International Space Station international partners are working to develop docking load attenuation systems compatible with International Docking System Standard requirements for both low-Earth orbit (LEO) and beyond-Earth orbit missions and environments.

Parameter, Value:

Docking and berthing systems currently in-use are designed and qualified for mating existing NASA and international partner spacecraft in the LEO environment.

TRL
4

Technology Performance Goal: Docking system with a standardized mating interface that will enable spacecraft across a wide range of mass properties to dock in LEO and beyond-Earth orbit environments, providing common transfer interfaces for crew, pressurized cargo, data, commands, electric power, and fluids.

Parameter, Value:

Eliminate or minimize the need for spacecraft or mission-unique docking systems and docking adapters, while maximizing capabilities for crew, cargo, electrical, and fluid transfers across docking interfaces.

TRL
9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: To securely attach to and transfer crew, fluids, cargo, etc. on all missions.

Capability Description: Development of docking system that will enable NASA and its partners to dock spacecraft of all anticipated masses for beyond-Earth orbit missions.

Capability State of the Art: Spacecraft docking and berthing systems currently in-use are the probe-and-drogue docking system and the common berthing mechanism berthing interface system.

Parameter, Value:

Docking and berthing systems currently in-use are designed and qualified for mating existing NASA and international partner spacecraft in the LEO environment.

Capability Performance Goal: Docking system with a standardized mating interface that will enable spacecraft across a wide range of mass properties to dock in LEO and beyond-Earth orbit environments, providing common transfer interfaces for crew, pressurized cargo, data, commands, electric power, and fluids.

Parameter, Value:

Docking system with a standardized mating interface that will enable spacecraft across a wide range of mass properties to dock in LEO and beyond-Earth orbit environments.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

12.3 Mechanical Systems
12.3.1 Deployables, Docking, and Interfaces

12.3.1.2 Low Shock Release Device

TECHNOLOGY

Technology Description: Verifiable, resettable, fast acting release device that reduces shock vibration.

Technology Challenge: Increase performance of release mechanisms. Modeling of shock environments.

Technology State of the Art: Existing release devices afford potential for high shock and are difficult to model, requiring testing. Ancillary devices are often required to manage shock loads and vibrations.

Parameter, Value:	TRL
High disturbance forces associated with current release mechanisms.	2

Technology Performance Goal: Low shock release mechanism for highly reliable restraint and release of deployable devices. Test correlated modeling of release mechanism's operation and performance.

Parameter, Value:	TRL
Lower disturbance forces – eliminating ancillary components (for example, attenuation, dampening, etc.); Demonstrated ability to model resulting in decreased testing.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low shock, single use, and multiple use release.

Capability Description: Provide low shock, low mass, and highly reliable means of restraint and release devices for interfaces and spacecraft.

Capability State of the Art: High shock environments for current release devices may require extensive experimental tests and simulations to define environments.

Parameter, Value:

High disturbance forces – requiring ancillary components (for example, attenuation, dampening, etc.);

Inability to model resulting in extensive testing.

Capability Performance Goal: Low shock, low mass, and highly reliable means of restraint and release of interfaces, systems, spacecraft. Test correlated modeling of release device operation and performance.

Parameter, Value:

Lower disturbance forces – eliminating ancillary components (for example, attenuation, dampening, etc.);

Demonstrated ability to model resulting in decreased testing.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years
Discovery: Discovery 14	Enhancing	--	2023	2020	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

12.3 Mechanical Systems
12.3.1 Deployables, Docking, and Interfaces

12.3.1.3 Deployment of Flex Material

TECHNOLOGY

Technology Description: Mechanism that can reliably deploy a wide variety of structural members.

Technology Challenge: Uncertainty of how membranes stow and how they respond in the actual environment, as well as accurately predict their deployed shape.

Technology State of the Art: Utilization underway in future telescope sun shield, yet advancements in this could have high payoffs in multitude of future designs.

Parameter, Value:
Limited experience with deployment of flex materials.

TRL
4

Technology Performance Goal: Large deployed system to overcome launch vehicle constraints (solar sails, gossamer reflectors). Perform scale testing and model correlation leading to full scale testing. Will eventually require zero-gravity testing to complete model correlation.

Parameter, Value:
Highly reliable deployment.

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Deploy large rigid deployable structure.

Capability Description: Deploy large, flexible system in space.

Capability State of the Art: Inflatable deployment is based on structural booms deployed from mechanisms. The mechanical packaging technique appears to be based on folding the long narrow material into flat panels so that the stowed volume was rectangular in geometry.

Parameter, Value:
Limited experience with deployment of flex materials.

Capability Performance Goal: Large deployed system to overcome launch vehicle constraints (solar sails, gossamer reflectors). Perform scale testing and model correlation leading to full scale testing. Will eventually require zero gravity testing to complete model correlation.

Parameter, Value:
Highly reliable deployment

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Discovery: Discovery 14	Enhancing	--	2023	2020	5 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

12.3 Mechanical Systems
12.3.1 Deployables, Docking, and Interfaces

12.3.1.4 Large Lightweight Stiff Deployable Packaging Technique

TECHNOLOGY

Technology Description: Packaging technique for large lightweight rigid deployable structures.

Technology Challenge: Limited volume of current orbit delivery systems relative to desired size of deployed systems.

Technology State of the Art: Has been developed for smaller systems previously, but is required for larger systems.

Parameter, Value: Packaging efficiency: packaging in smaller volumes.

TRL: 2

Technology Performance Goal: Technique enables the constituent materials for a space structure to be launched in an extremely compact form, approaching perfect packing efficiencies, and processed on-orbit to form structures optimized for the microgravity space environment, rather than launch environments.

Parameter, Value: Efficient packaging of deployables, optimized for the microgravity space environment, rather than launch environments.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Space structure with a launch configuration that is significantly smaller than it’s space deployed configuration.

Capability Description: Overcome the constraints of launch vehicle fairing size.

Capability State of the Art: The sizes of apertures and spacecraft structures are limited by the requirement to stow them within available launch fairings.

Parameter, Value: Packaging efficiency: packaging in smaller volumes.

Capability Performance Goal: Technique enables the constituent materials for a space structure to be launched in an extremely compact form, approaching perfect packing efficiencies, and processed on-orbit to form structures optimized for the microgravity space environment, rather than launch environments.

Parameter, Value: Efficient packaging of large deployables, optimized for the microgravity space environment, rather than launch environments.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years
Discovery: Discovery 14	Enhancing	--	2023	2020	5 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	5 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

12.3 Mechanical Systems
12.3.1 Deployables, Docking, and Interfaces

12.3.1.5 Mechanism for Auto Precision Landing Hazard Avoidance

TECHNOLOGY

Technology Description: Real-time response to landing hazards.

Technology Challenge: Mechanism integration that allows autonomous spacecraft assessment of several landing parameters.

Technology State of the Art: Portions currently worked under attenuation systems, but further developments needed to encompass auto select feature changes dependent upon actual terrain and environment encountered.

Parameter, Value:
Currently limited use of mechanisms for auto precision landing.

TRL 2

Technology Performance Goal: Perform interrelation of mechanisms testing in varying environments and terrains

Parameter, Value:
Real-time assessment of conditions enabling autonomously landing.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Enables navigation system to maneuver to a safe landing area.

Capability Description: Autonomously land safely, reliably, and with high precision in nominal and off-nominal conditions.

Capability State of the Art: Avoid hazards during landing operations; autonomous landing and hazard avoidance technology.

Parameter, Value:
Currently limited use of mechanisms for auto precision landing.

Capability Performance Goal: Perform interrelation of mechanisms testing in varying environments and terrains.

Parameter, Value:
Real-time assessment of conditions enabling autonomously landing.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years
Planetary Flagship: Europa	Enabling	--	2022*	2019	5 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

12.3 Mechanical Systems
12.3.1 Deployables, Docking, and Interfaces

12.3.1.6 Precision Structure Deploy Mechanism

TECHNOLOGY

Technology Description: Design of high precision hinge and latch for large structure.

Technology Challenge: Repeatability and predictability of stowing and deploying large structure from a small launch package to very high tolerances.

Technology State of the Art: In general, optomechanical designs focus on positioning devices and kinematic mounts for optical system components. There has been little to no design of hinges and latches for large deployable precision structures.

Parameter, Value: Existing latching and actuation technology is imprecise, unstable, and too expensive for use in many NASA missions. Large reflectors, mirrors, telescopes, and other position sensitive instruments.

TRL: 4

Technology Performance Goal: Develop requirements, test and perform model correlation to show tolerance feasibility.

Parameter, Value: Accurate, stable, and inexpensive latching and actuation technologies.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High precision deployment mechanisms for optical instruments.

Capability Description: Deploying large combinations of flexible and lightweight stiff mechanical systems with precise and repeatable results.

Capability State of the Art: Virtually all optical information gathering instruments benefit from greater aperture. For space-based instruments whose geometries are constrained by the launch vehicle, increasing the aperture requires deployment of some aspect of the optical train and then the precise and dynamically stable latching of the deployed components into defined positions.

Parameter, Value: Existing latching and actuation technology is too inaccurate, unstable, and expensive for use in many NASA missions. Large reflectors, mirrors, telescopes and other position sensitive instruments.

Capability Performance Goal: Develop requirements, and test and perform model correlation to show tolerance feasibility.

Parameter, Value: Accurate, stable, and inexpensive latching and actuation technologies.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Exoplanet Direct Imaging Mission	Enhancing	--	2030*	2025	5 years
Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enabling	--	2035*	2030	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

12.3 Mechanical Systems
12.3.2 Mechanism Life Extension Systems

12.3.2.1 Long-Life Bearing / Lube System

TECHNOLOGY

Technology Description: Improve bearing performance and life through advanced design, materials, lubricants, and relubrication system.

Technology Challenge: Overcoming life-limiting properties of current lubrication and components as well as the pitfalls associated with harsher environments of dust and cryogenic.

Technology State of the Art: Reduce friction through lubrication, precision fabrication, and/or non-contact means.

Parameter, Value:	TRL
Extending the life of the bearing; Reduced wear.	2

Technology Performance Goal: Demonstrate life testing in harsh environments with new lubrication and components.

Parameter, Value:	TRL
Improved performance lifetime of bearing and lubricant system in harsh environments.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Provide long-life bearings that operate in extreme or harsh environments.

Capability Description: Increase life for longer-duration missions and increased life for harsh environments.

Capability State of the Art: Bearing and lubricant system are limiting the life of space mechanisms.

Parameter, Value:
Limited life of bearing/lubricant system.

Capability Performance Goal: Develop and/or demonstrate reliable long life bearing and lubricant system of longer duration missions in harsh environments.

Parameter, Value:
Improved performance lifetime of bearing/lubricant system.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

12.3 Mechanical Systems
12.3.2 Mechanism Life Extension Systems

12.3.2.2 Cryo Long Life Actuator

TECHNOLOGY

Technology Description: Provide long-life actuator for cryogenic valves and couplings that operate in long-duration vacuum conditions with deep thermal cycles.

Technology Challenge: Severe low-temperature environments and their effect on current lubrications and actuator designs.

Technology State of the Art: Extending the life of the cryo actuator.

Parameter, Value:
Long life actuators that operate in cryo environments.

TRL 4

Technology Performance Goal: Improved performance lifetime of cryo actuator.

Parameter, Value:
Long life actuators that operate in cryo environments.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Provide long-life mechanisms that operate in cryogenic environments.

Capability Description: Limited lifetime actuators in operating cryo environments.

Capability State of the Art: Limited life of cryo actuator.

Parameter, Value:
The functioning life of actuators in cryo environment.

Capability Performance Goal: Improved performance lifetime of cryo actuator.

Parameter, Value:
Long life actuators that operate in cryo environments.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.3 Mechanical Systems
12.3.3 Electro-Mechanical, Mechanical, and Micromechanisms

12.3.3.1 Robotic Assembly Tools / Interfaces

TECHNOLOGY

Technology Description: Tools for robotic assets to cut, grasp, and turn for assembly and maintenance of structures.

Technology Challenge: Complexity and sheer number of systems required for the wide array of tools and systems needed.

Technology State of the Art: Multitudes of items have flown and are in development currently. Many are still required.

Parameter, Value: | **TRL**
Complexity of the task: currently able to complete simple tasks. | 2

Technology Performance Goal: Complete development and testing of tools or interfaces allowing increased complexity of tasks.

Parameter, Value: | **TRL**
Increase the complexity of tasks. | 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Robotic servicing, construction, and refueling missions.

Capability Description: Address the development of tools and interfaces that will allow robotic assembly, manipulation, and servicing of spacecraft and spacecraft components.

Capability State of the Art: In-situ build-up and repair of deep space missions and servicing of low-Earth orbit (LEO) satellites.

Parameter, Value:
Complexity of the task: currently able to complete simple tasks.

Capability Performance Goal: Complete development and testing of tools and interfaces allowing increased complexity of tasks.

Parameter, Value:
Increase the complexity of tasks.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.3 Mechanical Systems
12.3.3 Electro-Mechanical, Mechanical, and Micromechanisms

12.3.3.2 Cryogenic and Fluid Transfer

TECHNOLOGY

Technology Description: Automated fluid coupling design that operates under cryogenic conditions in space.

Technology Challenge: Design robustness to withstand deep thermal cycles, thermal mismatches, misalignment tolerances, seal integrity challenges while providing mission-critical function.

Technology State of the Art: To date, no automated fluid coupling system has been demonstrated for cryogenic applications. Technology Readiness Level (TRL) for flight fluids transfer is above 6. TRL level for cryogenic applications is 2 to 3.

Parameter, Value:

Only low-fidelity prototypes with minimal cryogenic exposures have been tested.

TRL 2

Technology Performance Goal: Establish space-capable design for automated fluid coupling capable of vacuum duty with solar heating (unmated) and rapid chill-down (minutes) and rapid transfer (hours).

Parameter, Value:

Seal integrity and leakage is threatened by deep thermal cycles, long unmated periods, and potential misalignment during mating.Reliability is challenged by mass constraints versus need for redundancy in actuators and drives.

TRL 3

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Autonomously transfer subcritical cryogenic propellants from one vehicle to another in microgravity.

Capability Description: Assure that subcritical cryogenic liquids can be stored and transferred from a donor vehicle to a receiver vehicle in space (for example, depleted stages, depots, tankers, and systems utilizing propellants produced in-situ on the Moon, Mars, etc.).

Capability State of the Art: NASA's robotic refueling mission investigation demonstrates and tests the tools, technologies, and techniques needed to robotically service and refuel non-cryogenic satellites in space.

Parameter, Value:

Reliability and complexity of the design with flight mass restrictions and extreme operating environments and lifetimes. Currently able to automate transfer in ground operations under controlled conditions.

Capability Performance Goal: Complete development of automated fluid coupling system and demonstrate in relative environment and for lifetime required.

Parameter, Value:

Value varies by mission requirements. Need operational couplings capable of remaining unmated for months in simulated space environment and then mating and transferring full cryogenic loads within hours or days.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.3 Mechanical Systems
12.3.4 Design and Analysis Tools and Methods

12.3.4.1 Interrelated Correlated Analysis System

TECHNOLOGY

Technology Description: Using evolutionary algorithms for solving multi-objective problems.

Technology Challenge: Identifying degree of interrelation and correlation needed for general classes of applications (for example, serial simulations may be sufficient for aspects of some applications while others may require direct co-simulation of two non-linear codes); and computational methods for combining dissimilar numerical techniques, including nonlinear analyses. Efficient integration of these systems with a health management system.

Technology State of the Art: Not currently being worked.

Parameter, Value: Limited use. Mainly used to optimize to a general solution. Individual analytical tools are used to confirm solution.

TRL: 1

Technology Performance Goal: Complete interrelation and correlation of analysis systems. Integrate health management system into overall analysis system. Prove accuracy of system via testing.

Parameter, Value: Interrelated correlated analysis system are used for the final solution.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: One master model for all discipline analysis modeling.

Capability Description: Combines numerical analysis methods of different disciplines to enable the creation of a single model of spacecraft mechanical systems in lieu of multiple iterative cycles of serial analyses.

Capability State of the Art: Reduction of overall stack-up of margins across disciplines (for example, aero loads, vehicle dynamics, structural response); and efficient vehicle or component diagnosis, prognosis, and performance assessment when implemented with a health management system. Stepping stone to Virtual Digital Fleet Leader.

Parameter, Value: Limited use. Mainly used to optimize to a general solution. Individual analytical tools are used to confirm solution.

Capability Performance Goal: Complete interrelation and correlation of analysis systems. Integrate health management system into overall analysis system. Prove accuracy of system via testing.

Parameter, Value: Interrelated correlated analysis system are used for the final solution.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.3 Mechanical Systems
12.3.5 Reliability, Life Assessment, and Health Montioring

12.3.5.1 Predictive Damage Method

TECHNOLOGY

Technology Description: Damage prediction using experimental and numerical methods.

Technology Challenge: Accurate determination of manufactured and damaged residual strength of mechanical systems.

Technology State of the Art: No current activity at NASA.

Parameter, Value: Measure cumulative damage; testing.

TRL: 1

Technology Performance Goal: Perform testing and model correlation determinations of residual strength.

Parameter, Value: Move away from testing toward probabilistic design to predict damage.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Predict using probabilistic methods.

Capability Description: Measure physical properties of mechanical systems as manufactured and after damage.

Capability State of the Art: Development of more efficient configurations and reduced reliance on testing compared to current practice.

Parameter, Value: Measure cumulative damage; testing.

Capability Performance Goal: Perform testing and model correlation determinations of residual strength.

Parameter, Value: Move away from testing toward probabilistic design to predict damage.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.3 Mechanical Systems
12.3.5 Reliability, Life Assessment, and Health Montioring

12.3.5.2 Embedded System

TECHNOLOGY

Technology Description: Sensors embedded in the mechanisms.

Technology Challenge: Miniaturizing and incorporating sensors technology as an integral part of mechanical systems and accurate correlation of system feedback.

Technology State of the Art: Deployed and commercial systems. Health monitoring being researched at NASA with other government agencies.

Parameter, Value:
Limited ability to perform real-time monitoring of health systems.

TRL: 3

Technology Performance Goal: Complete sensor development and perform testing and model correlation.

Parameter, Value:
Real-time monitoring of health systems.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Real time monitoring of mechanism performance.

Capability Description: Provide predictive and condition-based monitoring and prediction of mechanical systems to extend life, avoid failures, and assist system operations.

Capability State of the Art: Sensing actual loads and other parameters. Have “finger on the pulse” of the system or vehicle.

Parameter, Value:
Limited ability to perform real-time monitoring of health systems.

Capability Performance Goal: Complete sensor development and perform testing, and model correlation.

Parameter, Value:
Real-time monitoring of health systems.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.3 Mechanical Systems
12.3.5 Reliability, Life Assessment, and Health Montioring

12.3.5.3 Life Extension Prediction Method

TECHNOLOGY

Technology Description: Methods and procedures for predicting remaining life of mechanisms.

Technology Challenge: Determination of actual cumulative damage as well as establishment of accurate life predictions.

Technology State of the Art: Heavy reliance on testing for life predictions.

Parameter, Value:
Measure cumulative damage; testing.

TRL: 1

Technology Performance Goal: Complete accurate representation of operating environments relative to assessment of cumulative damage. Complete testing and correlation.

Parameter, Value:
Move away from testing toward probabilistic design to predict life.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Assess cumulative damage to predict life.

Capability Description: Provide current-state system life predictions based on cumulative damage assessments and actual operating environment conditions.

Capability State of the Art: Facilitated design and sustainment of the structure. Concepts incorporating an intrinsic repair capability are a long-term goal.

Parameter, Value:
Measure cumulative damage; testing.

Capability Performance Goal: Complete accurate representation of operating environments relative to assessment of cumulative damage. Complete testing and correlation.

Parameter, Value:
Move away from testing toward probabilistic design to predict life.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.3 Mechanical Systems
12.3.5 Reliability, Life Assessment, and Health Montioring

12.3.5.4 Integrated Health Monitoring System

TECHNOLOGY

Technology Description: Integrating all health monitoring systems.

Technology Challenge: Standardization of interfaces.

Technology State of the Art: Some testing is being done where systems are side by side to help with correlation, but current efforts of integration are minimal.

Parameter, Value: Limited ability to integrate health monitoring systems with life assessment.

TRL: 2

Technology Performance Goal: Perform standardization and integration of interfaces and systems. Verify accuracy through testing.

Parameter, Value: Integrate health monitoring systems with life assessment.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Fully digital representation utilizing actual mechanism data to predict how the spacecraft will behave.

Capability Description: Provide standard, integrated health monitoring systems for all vehicle systems and subsystems.

Capability State of the Art: Health-monitoring interfaces at all levels.

Parameter, Value: Limited ability to integrate health monitoring systems with life assessment.

Capability Performance Goal: Perform standardization and integration of interfaces and systems. Verify accuracy through testing.

Parameter, Value: Integrate health monitoring systems with life assessment.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.3 Mechanical Systems
12.3.6 Certification Methods

12.3.6.1 Verified Physics Modeling Tool

TECHNOLOGY

Technology Description: Analytical modeling of complex and integrated system failure modes.

Technology Challenge: Modeling mechanical systems failure modes such that a system can be designed virtually with the highest probability of success.

Technology State of the Art: Limited ability to model system failure modes preventing virtual design.

Parameter, Value:

Low level of confidence in analytical models, high reliance on test results.

TRL 1

Technology Performance Goal: Accurately determine failure modes of mechanisms. Test and correlate models.

Parameter, Value:

High level of confidence in analytical models, low reliance on test results.

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Ability to model mechanical system modes allowing for virtual design.

Capability Description: Provide model-based design of mechanical systems with increased design confidence and reliability.

Capability State of the Art: Limited ability to accurately predict system failures ahead of hardware build and life test.

Parameter, Value:

Low level of confidence in analytical models, high reliance on test results.

Capability Performance Goal: Accurately determine failure modes of mechanisms. Test and correlate models.

Parameter, Value:

High level of confidence in analytical models, low reliance on test results.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

12.3 Mechanical Systems
12.3.6 Certification Methods

12.3.6.2 Virtual Probabilistic Design Model

TECHNOLOGY

Technology Description: Virtual evaluation of design based on failure modes (statistical methods).

Technology Challenge: Obtaining the needed test data for various mechanical systems and performance parameters to develop preferred options for hardware design.

Technology State of the Art: Limited ability to accurately evaluate integrated mechanical system reliability. Historical, component-based probabilistic risk assessment methods used. A single life test with a high factor.

Parameter, Value: Low level of confidence in analytical models, high reliance on single tests with high margin.

TRL: 1

Technology Performance Goal: Reliably determine failure modes of mechanisms and correlate analytical models.

Parameter, Value: Improved reliability base on multiple tests with reduced uncertainty factors.

TRL: 5

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Ability to design mechanisms without excessive life margin.

Capability Description: Utilizes test data from multiple units and performance parameters to develop optimized hardware design.

Capability State of the Art: Shift away from expensive tests and verify by correlated analytical data. Reductions in cost and design schedule are evident through meeting functionality requirements with the first hardware build.

Parameter, Value: Low level of confidence in analytical models, high reliance on test results.

Capability Performance Goal: Reliably determine failure modes of mechanisms and correlate analytical models.

Parameter, Value: High level of confidence in life prediction, reliance on statistical confidence of testing.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

12.3 Mechanical Systems
12.3.6 Certification Methods

12.3.6.3 Digital Certification Method in Cyberspace

TECHNOLOGY

Technology Description: Virtual incorporation of test verified physics, and probabilistic design.

Technology Challenge: Digitally certifying physical system parameters.

Technology State of the Art: Not currently being worked. Precursor to Virtual Digital Fleet Leader.

Parameter, Value: Low level of confidence in analytical models, high reliance on test results.

TRL: 1

Technology Performance Goal: Accurately determine failure modes of mechanisms. Test and correlate models.

Parameter, Value: High level of confidence in analytical models, low reliance on test results.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Virtual ability to certify systems designs.

Capability Description: The precursor to the Virtual Digital Fleet Leader. In order to have a complete digital system, there must be an ability to certify subsystems in cyberspace. This is envisioned through the use of hardware health monitoring and telemetry systems that can help to correlate mechanism performance models.

Capability State of the Art: Correlation of mechanism performance models which will ultimately eliminate the cost of large deployable or other mechanical systems testing.

Parameter, Value: Low level of confidence in analytical models, high reliance on test results.

Capability Performance Goal: Accurately determine failure modes of mechanisms. Test and correlate models.

Parameter, Value: High level of confidence in analytical models, low reliance on test results.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

12.3 Mechanical Systems
12.3.6 Certification Methods

12.3.6.4 Virtual Digital Fleet Leader System Certification

TECHNOLOGY

Technology Description: The digital representation of the flight system with comprehensive diagnostic and prognostic capabilities to enable efficient development and certification as well as safe, autonomous operation throughout the service life of system.

Technology Challenge: Development of a digital representation of the entire spacecraft through the integration of high-fidelity and certification models, service life inspection and health monitoring assessment data, and life extension prediction methods in a real-time framework.

Technology State of the Art: Not currently being worked.

Parameter, Value: (TRL 1)
Low level of confidence in analytical models, high reliance on test results.

Technology Performance Goal: Autonomous predictions of mechanism failure modes.

Parameter, Value: (TRL 5)
High level of confidence in analytical models, low reliance on test results.

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Virtual ability to certify systems designs.

Capability Description: Eliminate the cost of large deployable or other mechanical systems testing leading to the Virtual Digital Fleet Leader.

Capability State of the Art: Full-up digital representation of vehicle. Provides real-time assessment of vehicle for use in predicting the best next maneuver.

Parameter, Value:
Low level of confidence in analytical models, high reliance on test results.

Capability Performance Goal: Accurately determine failure modes of mechanisms. Test and correlate models.

Parameter, Value:
High level of confidence in analytical models, low reliance on test results.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

12.4 Manufacturing
12.4.1 Manufacturing Processes

12.4.1.1 Innovative Metallic Process

TECHNOLOGY

Technology Description: Critical, high-value process (for example, solid-state joining, additive manufacturing, near-net shape forming).

Technology Challenge: Develop large-scale metallic materials processing and pervasive automation to improve productivity and mechanical performance.

Technology State of the Art: Emerging large-scale metallic materials, processing, and pervasive automation to reduce fabrication and assembly costs and provide recyclability.

Parameter, Value:
Limited automation, specifications and standards, and process qualifications.

TRL 4

Technology Performance Goal: Mature and qualified automation process.

Parameter, Value:
Productivity and mechanical performance.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Materials research and computational materials engineering. Integrated design and metals processing.

CAPABILITY

Needed Capability: High-productivity, improved performance, and metallic fabrication.

Capability Description: Provide automated manufacturing techniques that will reduce cost and improve performance (for example, productivity, mechanical performance).

Capability State of the Art: Current practice is costly and inefficient with many individual manual processes.

Parameter, Value:
Productivity and mechanical performance.

Capability Performance Goal: Improved performance and lower cost.

Parameter, Value:
Productivity and mechanical performance.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.4 Manufacturing
12.4.1 Manufacturing Processes

12.4.1.2 Polymer Matrix Composite (PMC) Process

TECHNOLOGY

Technology Description: PMC process that results in large composite structures that have required performance for space applications.

Technology Challenge: Develop manufacturing scale-up, process for cryotanks, and high temperature materials, automation to reduce fabrication and assembly costs.

Technology State of the Art: High rate robotic fiber placement systems and out-of-autoclave materials to reduce fabrication and assembly costs.

Parameter, Value:
Limited automation, specifications and standards, and process qualifications.

TRL 4

Technology Performance Goal: Mature and qualified automation process.

Parameter, Value:
Productivity and mechanical performance.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Materials research and computational materials engineering. Integrated design and processing.

CAPABILITY

Needed Capability: Composite process for large composite structures.

Capability Description: Develop advanced composites process (for example, non-autoclave). Provide automated manufacturing techniques that will reduce cost and improve performance (for example, productivity, mechanical performance).

Capability State of the Art: Automated fiber placement and autoclave cure is predominate method. Current practice is costly and inefficient with many individual or manual processes.

Parameter, Value:
Relative time and cost. Productivity and mechanical performance.

Capability Performance Goal: Improved performance, lower cost. Achieve higher rates with comparable quality. Utilize out-of-autoclave for large structures.

Parameter, Value:
Productivity and mechanical performance.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.4 Manufacturing
12.4.1 Manufacturing Processes

12.4.1.3 Ceramic Matrix Composite (CMC) Process

TECHNOLOGY

Technology Description: CMC process that results in large composite structures that have required performance for space applications.

Technology Challenge: Consistent properties, scale-up for size, complex curvature, and integration.

Technology State of the Art: Very limited production.

Parameter, Value:
Low mechanical performance.

TRL
3

Technology Performance Goal: Mature and qualified process.

Parameter, Value:
Improved mechanical performance.

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Materials research and computational materials engineering. Integrated design and metals processing.

CAPABILITY

Needed Capability: CMC processes for high-temperature composite structures.

Capability Description: High-quality manufacturing consistency.

Capability State of the Art: Limited in scale, hypersonic leading edge, small liquid engine nozzles.

Parameter, Value:
Mechanical performance.

Capability Performance Goal: Improve higher quality manufacturing consistency.

Parameter, Value:
Mechanical performance.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.4 Manufacturing
12.4.1 Manufacturing Processes

12.4.1.4 In-Space Assembly, Fabrication, and Repair Process

TECHNOLOGY

Technology Description: In-space assembly, fabrication, and repair (ISAFR) process that results in large composite or metallic structures that have required performance for space applications.

Technology Challenge: New devices for replacing parts or building new parts in space.

Technology State of the Art: Limited repair kits for extravehicular activity (EVA) repair of pressure leaks of space station modules and Shuttle thermal protection system.

Parameter, Value:	TRL
Limited development, specifications and standards, and process qualifications	3

Technology Performance Goal: Mature development, specifications and standards, and process qualifications.

Parameter, Value:	TRL
Structural performance, in relevant environment, and system mass	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Microgravity research and scale-up.

CAPABILITY

Needed Capability: In-space assembly, fabrication, and repair process for large composite structures.

Capability Description: Introduction of new materials and methods to fabricate structures in-space. Provide techniques that will reduce cost and improve performance (for example, productivity, mechanical performance).

Capability State of the Art: Current practice is very limited. Limited to International Space Station assembly, with extremely limited fabrication and repair.

Parameter, Value:

Mechanical performance.

Capability Performance Goal: Develop and demonstrate prototype process and system.

Parameter, Value:

Structural performance in relevant environment and system mass.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years

12.4 Manufacturing
12.4.2 Intelligent Integrated Manufacturing and Cyber Physical Systems

12.4.2.1 Digital and Model-Based Manufacturing

TECHNOLOGY

Technology Description: 'Digital thread' that integrates modern design, manufacturing, and product support processes.

Technology Challenge: Research for emerging methodologies for digital product life-cycle model framework emergent data mining capabilities leverage information from disparate areas, enable model driven equipment and operations to autonomously recognize and respond.

Technology State of the Art: Digital twin; full-knowledge of the design, manufacturing, and operations supply chain.

Parameter, Value: Limited and fragmented model-based practices.

TRL 4

Technology Performance Goal: Mature and qualified model-based process

Parameter, Value: Pervasive and qualified model-based practices.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Advanced information technology tools, models, sensors, controls, practices, and skills.

CAPABILITY

Needed Capability: Model-based manufacturing capability across the manufacturing life-cycle.

Capability Description: Mathematically accurate models that are linked to manufacturing; digital product definition contains complete design and manufacturing information; terrestrial and in-space collaborative supply networks; process development; and manufacturing simulation.

Capability State of the Art: Lack of integrated data stream or decision-making, and lack of life-cycle analysis and efficiencies for product development, manufacturing, and sustainment.

Parameter, Value: Productivity and reliable products.

Capability Performance Goal: Improved performance and lower cost. Develop and demonstrate model based prototype processes and systems.

Parameter, Value: Productivity and reliable products.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.4 Manufacturing
12.4.2 Intelligent Integrated Manufacturing and Cyber Physical Systems

12.4.2.2 Model-Based Operations

TECHNOLOGY

Technology Description: Development and integration of smart sensors, controls, and measurement, analysis, decision, and communication software tools for factory machines.

Technology Challenge: Science-based manufacturing environment that enables the virtual evaluation and set-up of new processes and equipment.

Technology State of the Art: Digital twin is in concept stage, but constituent capabilities are in various stages of development.

Parameter, Value: Limited and fragmented model-based practices.

TRL 4

Technology Performance Goal: Mature and qualified model-based processes.

Parameter, Value: Pervasive and qualified model-based practices.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Advanced information technology tools, models, sensors, controls, practices, and skills.

CAPABILITY

Needed Capability: Model-based production functionality and allowing equipment to use manufacturing knowledge while planning and processing products.

Capability Description: Integrates factory, process, reliability, and equipment models.

Capability State of the Art: Currently does not take advantage of data from different sources; models developed late; models from different sources not integrated.

Parameter, Value: Productivity and reliable products.

Capability Performance Goal: Develop prototype model correlation process that incorporates full field data.

Parameter, Value: Productivity and reliable products.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.4 Manufacturing
12.4.2 Intelligent Integrated Manufacturing and Cyber Physical Systems

12.4.2.3 Additive Manufacturing

TECHNOLOGY

Technology Description: Additive manufacturing processes for space and in-space.

Technology Challenge: Science-based manufacturing environment that enables the virtual evaluation and set-up of new processes and equipment.

Technology State of the Art: Now testing additive manufacturing for making engine parts for the Space Launch System.

Parameter, Value: Limited development, specifications and standards, and process qualifications.

TRL 4

Technology Performance Goal: Mature and qualified additive processes.

Parameter, Value: Productivity and mechanical performance.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Detailed understanding of processing conditions and the interrelationship with properties, performance, and potential flaw types, sizes, and populations.

CAPABILITY

Needed Capability: Additive manufacturing for size and weight optimized components and subsystems, components and subsystems which are challenging to traditionally fabricate, multifunctional structures, propulsion, and in-space structures.

Capability Description: Introduction of additive manufacturing to fabricate structures and products for terrestrial launch vehicle, spacecraft components and subsystems, and in-space applications.

Capability State of the Art: Emerging use in industry, not certified for spaceflight.

Parameter, Value: Productivity and mechanical performance.

Capability Performance Goal: Improved performance, lower cost, reduced development time. Develop and qualify additive processes and systems.

Parameter, Value: Productivity and mechanical performance.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.4 Manufacturing
12.4.3 Electronics and Optics Manufacturing Process

12.4.3.1 Photovoltaic Solar Cell Manufacturing

TECHNOLOGY

Technology Description: High efficiency solar cells production.

Technology Challenge: New cell fabrication processes that provide improved reliability, optical, thermal, and electrical performance.

Technology State of the Art: Triple-junction solar cells grown on germanium substrate.

Parameter, Value:
Efficiency: 29.5%

TRL: 9

Technology Performance Goal: Photovoltic cells production that yields high efficiency and reliably in a space environment with reduced mass over current cells.

Parameter, Value:
Efficiency: 35%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Provide processing for high efficiency solar cell production.

Capability Description: Photovoltaic technology is material and processes development for solar cells production.

Capability State of the Art: Photovoltaic cells currently in use have efficiency of 29.5% at air mass zero (AM0), 28° C at beginning of life.

Parameter, Value:
Efficiency: 29.5% at AM0, 28° C at beginning of life

Capability Performance Goal: Photovoltic cells production that that yields high efficiency and reliably in a space environment with reduced mass over current cells.

Parameter, Value:
Efficiency: 35%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years
Discovery: Discovery 14	Enabling	--	2023	2020	5 years

12.4 Manufacturing
12.4.3 Electronics and Optics Manufacturing Process

12.4.3.2 Optics Fabrication

TECHNOLOGY

Technology Description: Precision optic component materials and methods.

Technology Challenge: Improved technologies to manufacture optical quality mirrors and substrates.

Technology State of the Art: Single crystal of silicon is being grown into optical substrates.

Parameter, Value:
Areal density: 40 kg/m^2 at 25 nm root mean square (RMS).

TRL
4

Technology Performance Goal: Produce precision optics with substrates at lower areal mass density while meeting precision shape and surface finish requirements.

Parameter, Value:
Areal density: 20 kg/m^2 at 6 nm RMS.

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Material availability, in-situ metrology, mounting design, and good requirements definition of large launch vehicles to carry these aloft.

CAPABILITY

Needed Capability: Provide optics production materials and methodologies for precision optics.

Capability Description: Provide optics substrate materials, fabrication processes and verification metrology for X-ray, ultraviolet, infrared, and visible optics for space telescope systems.

Capability State of the Art: Monolithic beryllium substrates machined from billets.

Parameter, Value:
Areal density: 50 kg/m^2 at 25 nm RMS.

Capability Performance Goal: Produce precision optics with substrates at lower areal mass density while meeting precision shape and surface finish requirements.

Parameter, Value:
Areal density: 20 kg/m^2 at 6 nm RMS.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: X-ray Surveyor Mission	Enhancing	--	2035*	2030	5 years
Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enhancing	--	2035*	2030	7 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

12.4 Manufacturing
12.4.3 Electronics and Optics Manufacturing Process

12.4.3.3 Special Electrical Process

TECHNOLOGY

Technology Description: Electrical components production for extreme environments electronics.

Technology Challenge: Adopt and improve upon commercial models and processes for use in the production of affordable, advanced NASA systems.

Technology State of the Art: Commercially available development progress.

Parameter, Value:
Radiation and temperature rating; Cost per unit.

TRL 5

Technology Performance Goal: Improve on commercial models and processes for use in the production of affordable advanced NASA systems.

Parameter, Value:
Radiation and temperature rating;
Cost per unit.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Materials, test capabilities, and cooperation from commercial entities.

CAPABILITY

Needed Capability: Provide electronics production materials and methodologies.

Capability Description: Provide material and manufacturing processes for electronics in extreme temperature and radiation environments.

Capability State of the Art: Commercially available circuit board materials and manufacturing.

Parameter, Value:
Radiation and temperature rating;
Cost per unit.

Capability Performance Goal: More precise production models and processes for electronics production.

Parameter, Value:
Radiation and temperature rating;
Cost per unit.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Saturn Probe	Enhancing	--	2024	2016	2 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

12.4 Manufacturing
12.4.3 Electronics and Optics Manufacturing Process

12.4.3.4 Large Ultra-Light Precision Optical Structures

TECHNOLOGY

Technology Description: Optical structures, materials, and methods to build precision large space-based science instrument structures.

Technology Challenge: New materials and processes to manufacture ultra-lightweight precision optical systems for very large structures.

Technology State of the Art: 6.5 meter telescope assembly with near zero coefficient of thermal expansion material bonded into a truss shaped structure.

Parameter, Value:
Dimensional stability;
Unit mass

TRL 6

Technology Performance Goal: 10 meter optical telescope structure with higher assembly precision and reduced mass than James Webb Space Telescope for 20 K temperature operations.

Parameter, Value:
Dimensional stability;
Unit mass

TRL 3

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Optics materials, analyses capabilities, and good requirements definition of large launch vehicles to carry these aloft.

CAPABILITY

Needed Capability: Large aperture precise optical structures materials and methods.

Capability Description: Provide materials and methods to produce large aperture precision optical system structures.

Capability State of the Art: Near zero coefficient of expansion composite laminates are adhesively bonded into a truss shaped structure to mount 18 1.3 meter optical segments producing a 6.5 meter primary mirror assembly.

Parameter, Value:
Dimensional stability;
Unit mass

Capability Performance Goal: Precision optical structures technology performance goal is to maintain optical tolerances on a low mass structure.

Parameter, Value:
Dimensional stability;
Unit mass

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: X-ray Surveyor Mission	Enabling	--	2035*	2030	5 years
Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enabling	--	2035*	2030	7 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

12.4 Manufacturing
12.4.4 Sustainable Manufacturing

12.4.4.1 Environmental Technologies

TECHNOLOGY

Technology Description: Technologies that reduce or eliminate the use of hazardous materials in production processes; remove hazardous materials like hexavalent chromium and volatile organic compounds from manufacturing activities such as painting, coating, and cleaning; and green alternative energetic compounds.

Technology Challenge: Innovative methods to improve affordability and accelerate program schedules, new green processes, new materials, and replacement processes.

Technology State of the Art: Sustainable manufacturing, mitigates risks from obsolescence, enables resource efficiency and effectiveness, and long-term sustainability.

Parameter, Value: Limited development, specifications and standards, and process qualifications.

TRL 5

Technology Performance Goal: Mature developed, specifications and standards, and process qualifications.

Parameter, Value: Environmental performance.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Removing environmentally hazardous materials from manufacturing.

Capability Description: New and substitute environmentally sustainable processes.

Capability State of the Art: Sustainable design and manufacturing for products that minimize negative environmental impacts.

Parameter, Value: Environmental performance.

Capability Performance Goal: Sustainable design and manufacturing for products that minimize negative environmental effects. Comprehensive directed approach to emerging processing and manufacturing technologies.

Parameter, Value: Environmental performance.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

12.4 Manufacturing
12.4.5 Nondestructive Evaluation and Sensors

12.4.5.1 Nondestructive Evaluation (NDE) Sensor and Method

TECHNOLOGY

Technology Description: Computational nondestructive evaluation (NDE) method and process for propulsion and in-space structures.

Technology Challenge: Sensors and NDE methodologies for high-fidelity detection and characterization of flaws and degradation in complex built-up structures. Automated for manufacturing.

Technology State of the Art: Developmental and advanced industry systems.

Parameter, Value: Emerging but fragmented computational and autonomous practices.

TRL 4

Technology Performance Goal: Mature and qualified computational NDE processes.

Parameter, Value: Productivity and detection performance.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Computational NDE for propulsion and in-space structures.

Capability Description: Computational NDE, autonomous inspection, and real-time comprehensive diagnostics.

Capability State of the Art: Sensors and NDE methodologies for high fidelity detection and characterization of flaws and degradation in complex structures. Most methods are slow, labor intensive, and require highly skilled interpretation.

Parameter, Value: Productivity and detection performance.

Capability Performance Goal: Develop viable techniques for inspection and assurance of the integrity of complex built-up structures.

Parameter, Value: Productivity and detection performance.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years